TREE WRAPS AND MICROSPRINKLER IRRIGATION FOR FREEZE PROTECTION OF YOUNG CITRUS TREES

BY

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This dissertation is dedicated to my family members
and to the loving memory of Suzanne Lynn DiCenzo

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FREEZE PROTECTION OF YOUNG CITRUS TREES WITH TREE WRAPS AND MICROSPRINKLER IRRIGATION

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Tree wraps and microsprinkler irrigation provide a reliable and economical alternative to soil banks and orchard heaters for freeze protection of young citrus trees. Field experimentation and computer simulation were employed to study the freeze protection capabilities of tree wraps alone and in combination with microsprinkler irrigation. Trunk temperatures of 2-year-old 'Hamlin' orange (Citrus sinensis (L.) Osb.) trees during freeze conditions were greater for wrapped trees irrigated with a 90° spray pattern than for those irrigated at the same rate with a 360° spray pattern. An irrigation rate of 38 liters hr^{-1} provided the greatest increase in trunk temperature per unit water applied during several freezes. Air temperature, dewpoint and net radiation in the tree canopy were not increased by microsprinkler irrigation during freeze conditions, although soil temperature was 2° to 6° C higher for irrigated than for unirrigated trees.

Thermal properties of commonly used tree wraps were determined in the laboratory. Thermal diffusivity was lowest for styrofoam wraps with water containers, intermediate for 9-cm diameter fiberglass wraps, and highest for thin-walled polyethylene and polystyrene wraps. Thermal

diffusivity was indicative of freeze protection capability of tree wraps.

The simulation model of the tree wrap/microsprinkler system predicted trunk temperatures within 1° C of observed means when simulating the effect of tree wraps alone, although predictions generally were 1° to 3° C lower than observed means when simulating the irrigation process. The rate of air temperature decrease, wrap thickness and trunk diameter were positively correlated with level of freeze protection in computer simulations of fiberglass wraps; however, freeze duration was negatively correlated with level of freeze protection. Windspeed had little effect on trunk temperature of unirrigated wrapped trees, but trunk temperature of irrigated wrapped trees was reduced 5° C as windspeed increased from 0 to 10 m s^{-1}. Increasing the amount of water intercepted by the wrap and coverage of the wrap surface with water increased trunk temperature during simulated freezes. Temperature of the irrigation water was positively correlated with trunk temperature for radiative but not advective freeze conditions in simulations.

CHAPTER I
INTRODUCTION

Freeze damage of young citrus trees has been a problem since the establishment of the Florida citrus industry. Young trees are particularly prone to freeze damage due to their small size and vigorous growth habit. Citrus growers spend $18 to $42 and 3 to 4 years bringing a young tree into production (95). Traditionally, soil banks have been used for freeze protection of young citrus trees (59). Soil banks provide several degrees C protection to the lower portion of the tree, but are labor intensive and often result in mechanical or disease damage to the trunk. To avoid the problems associated with soil banks, Rohrbaugh designed the first insulative tree wrap, consisting of rock wool inside a 30-cm cylinder of asphalt felt which surrounded the lower 50 cm of a young tree (80). Results from preliminary tests with similar wraps appeared promising; however, the types of tree wraps used currently provide only 3° C protection in some cases, and virtually no protection in others (68, 121).

Overhead irrigation, petroleum fuel heaters, and wind machines have been used successfully to protect young and mature citrus trees. However, overhead irrigation systems often are not designed to apply water at rates necessary for protection under advective freeze conditions (46). Heating groves or nurseries with petroleum products is an effective means of cold protection, but rising fuel costs have limited the use of this practice to high cash value crops (107). Wind

machines rely on the presence of an inversion layer (45), and therefore are ineffective under advective freeze conditions.

A reliable and economical alternative to the conventional methods listed above for freeze protection of young citrus is low-volume microsprinkler irrigation. This system provides protection to the lower portion of the tree only, much like a soil bank. Previous studies have shown that trees irrigated with microsprinkers are usually killed above a height of 50 to 70 cm during severe freezes (30, 104). However, freeze-damaged trees often produce several vigorous shoots from the remaining portion of scion wood and attain heights of 1 to 2 m by the following autumn (104). The net result is that the grower loses about 6 months' growth on the tree but saves the cost of purchasing and resetting new trees, which is particularly important considering the scarcity and high prices of nursery trees due to the recent outbreak of citrus canker disease in Florida.

Microsprinkler irrigation has been reported to alter the microclimate of citrus plantings by raising the air temperature within the canopy (15), creating fog or mist, and/or decreasing radiant heat loss from the irrigated area (53, 107, 108). However, the effects of microclimatic changes on young citrus tree temperatures and subsequent freeze survival are unclear.

Recommendations regarding irrigation rate and spray pattern are currently lacking, although preliminary studies indicate that 76 to 84 liters hr^{-1} sprayed in a 90° pattern will protect young trees under most freeze conditions (30, 107). Davies et al. (30) suggest that microsprinkler irrigation combined with an insulative wrap provides greater protection for young citrus trees than irrigation or wraps used

separately. However, wraps left on freeze-damaged trees may reduce trunk sprouting and delay canopy reestablishment following a severe freeze. Further research with tree wraps and microsprinkler irrigation is needed to determine the effects of irrigation rate, spray pattern, and wrap type on trunk temperature, survival and sprouting of young citrus trees.

Modeling has been used successfully to predict overhead irrigation rates required for freeze protection of tree crops (20, 46, 112). Hence, modeling and simulation of the tree wrap/microsprinkler irrigation system of freeze protection may yield useful information on system design and behavior. Analysis of a model can produce information unobtainable from field or laboratory experiments due to uncontrolled or unrepresentative environmental conditions. Furthermore, experiments can be performed with a simulation model more rapidly and inexpensively than field experiments, improving the productivity and efficiency of the freeze protection research program.

Research objectives of this dissertation were

1. to study the effects of tree wraps combined with various microsprinkler irrigation rates and spray patterns on trunk temperature, survival and regrowth of young citrus trees;

2. to determine whether microsprinkler irrigation alters the microclimate of a young citrus tree during freeze conditions;

3. to determine the influence of various tree wraps on trunk temperature and sprouting of freeze-damaged trees;

4. to model the dynamic behavior of trunk temperature during freeze conditions as influenced by tree wraps and microsprinkler irrigation.

CHAPTER II
REVIEW OF THE LITERATURE

Introduction

Man's efforts to protect crops from freezing injury began at least 2000 years ago (83). In addition, the causes of freezing injury in plants have been studied and speculated upon for well over 100 years (124). Impetus for continued research in these areas stems from the huge economic losses of agricultural commodities that occur annually due to late spring or early fall frosts, or midwinter freezes. Literature on freezing injury, protection and related topics is voluminous. Several reviews (18, 75, 86, 91, 98, 116, 124, 135, 157, 167) and books edited by Levitt (76) Olien and Smith (99), and Li and Sakai (78) have covered various aspects of freezing stress and injury, and cold acclimation and hardiness. The intent of this review is to discuss general aspects freezing injury, resistance to freezing stress, and cold acclimation in woody plants with special attention to citrus. Herbaceous plants, with the exception of winter grasses (82), have little or no resistance to freezing stress or ability to acclimate and are therefore omitted. In addition, methods of freeze protection will be reviewed.

Freezing Injury, Stress, and Cold Acclimation

Freezing Injury

Freezing injury results from ice formation in plant tissues and not low temperatures per se (92). Manifestations of freezing injury include

sunscald and bark splitting of tree trunks, blackheart in trunks and stems, death and abscission of leaves, flowers, and fruits, frost rings on fruits, midwinter kill of dormant flower buds and stem cambia, and death of the entire vegetative structures of cold tender plants (18, 135, 136). These visual symptoms ultimately result from processes which occur at the cellular level.

Plant cells are injured or killed by either intracellular or extracellular ice formation (75). It is widely accepted that intracellular ice formation is always fatal to plant cells, although how intracellular freezing kills the cell remains unanswered (124). It follows that cells which survive freezing do so by tolerating extracellular ice formation. Therefore, much attention has been devoted to processes which occur during extracellular ice formation and the resulting consequences.

Extracellular freezing may be summarized as follows. As temperature decreases below 0° C, water in plant tissues initially supercools few to several degrees (18, 86). Heterogenous nucleation occurs in cell walls and extracellular spaces and ice crystals grow in these areas at the expense of water inside the cells (91, 92). As long as exosmosis of intracellular water keeps pace with the reduction in external vapor pressure with decreasing temperature, equilibrium between the intracellular solution and the external phase is maintained, and intracellular freezing is avoided by colligative freezing point reduction (86). However, supercooling and intracellular freezing are favored at rapid cooling rates ($> 10°$ C min^{-1}), especially if the permeability of the plasma membrane to water is low (85).

Extracellular freezing is tolerated to varying degrees in plant tissues depending on species, time of year, preconditioning, plant part, freezing rate and water content (135). Several hypotheses attempt to explain causes of cell death due to extracellular freezing. Levitt (74) hypothesized that intermolecular disulfide bonds formed among proteins with exposed sulfhydryl groups during freeze dehydration of cells by external ice. He stated that this resulted from the close proximity of proteins due to the reduced volume of cytoplasm. Williams (140) hypothesized that there was a minimum volume that cells attained during freeze dehydration below which cell death occurred. This minimum volume was the same for acclimated and unacclimated cells, but the temperature at which minimum volume was reached was lower for acclimated cells due to higher solute and bound water contents. Solution effects (i.e., concentration of toxic electrolytes, pH changes, precipitation of compounds, salting out of proteins) may result in injury to cell membranes and other cellular components during freeze dehydration (86, 124). Recently, the behavior of the plasma membrane during freezing was analyzed in isolated protoplasts (124). Apparently, vesiculation and deletion of membrane material occurs in unacclimated protoplasts, which causes altered osmotic behavior and cell lysis upon thawing, whereas these processes are not observed in acclimated protoplasts. Therefore, the plasma membrane may have an important role in cold acclimation and tolerance of extracellular ice. However, none of the above hypotheses are without limiting weaknesses, and no single hypothesis applies to all plant cells and all freezing situations.

Resistance to Freezing Stress

Resistance to freezing stress is conferred by avoidance and/or tolerance of ice formation within the plant (76).

Avoidance. Plants avoid freezing in low temperature environments by desiccation, colligative freezing point depression, and supercooling (75). Desiccation occurs in seeds and buds only, and freezing point depression allows avoidance of freezing to about -4° C at most. Alternatively, supercooling is a very effective avoidance mechanism, but usually occurs in plants which also tolerate extracellular ice formation (2, 42). One exception is shagbark hickory, which avoids freezing injury to -40° C by supercooling of the entire volume of liquid water in stems (18).

Tolerance. Reasons for difference in tolerance of extracellular ice among species are unknown, although apparently, hardier plants survive freezing of a larger amount of their osmotically active water (1, 16, 18).

The latitudinal range of a particular plant species is related to its relative tolerance of extracellular ice formation (17). Species which tolerate little extracellular ice such as citrus, are limited to southern latitudes where freeze events are less severe and occur infrequently. Temperate woody plants such as Vitis, Prunus, and Rhododendron tolerate extracellular ice in most tissues and avoid ice formation in flower bud primordia via deep supercooling (4, 42, 142). These plants are not found at latitudes where temperatures below about -40° C occur, because deep supercooled cells freeze and die at this temperature due to homogenous nucleation of intracellular water (17). Species of the northern boreal forests such as Betula and Populus do not

deep supercool, but tolerate freezing of all their osmotically active water outside the plasmalemma (18). These species are capable of surviving immersion in liquid nitrogen (-196° C) after slow cooling to -30° C.

Cold Acclimation

Irrespective of freezing tolerance mechanisms, temperate woody plants acclimate to low temperatures in 2 distinct stages. Stage I acclimation is a phytochrome-mediated response initiated by short days and enhanced by warm temperatures (38, 58, 64, 87). Moderate increases in hardiness occur during stage I acclimation (135). A translocatable "cold hardiness producing substance" presumed to be abscisic acid (63) has been shown to be involved in stage I acclimation (37, 66, 125). Stage II acclimation is initiated by exposure to low, nonfreezing temperatures or frost, and does not involve translocatable substances (37, 58). Plants acclimate rapidly and to their fullest potential during stage II acclimation.

Irving and Lanphear (64, 65) showed that woody plants would eventually acclimate to normal levels when exposed to long days and low temperatures, suggesting that low temperature has an overriding influence on photoperiod in cold acclimation. Furthermore, they showed that plants acclimate substantially before becoming dormant under long day, low temperature (10° C) conditions (64). Apparently, dormancy and cold hardiness are separate processes which occur coincidentally in the natural environment in woody perennials.

Tumanov and Krasavtsev (127) discovered a third stage of hardiness which develops during prolonged exposure to subfreezing temperatures, and is rapidly lost upon rewarming. They stated that prolonged exposure

to subfreezing temperatures allows sufficient time for water movement to extracellular sites which prevents intracellular freezing, whereas natural cooling rates are more rapid and result in supercooling and intracellular freezing at higher temperatures. Similarly, Rajashekar and Burke (118) found that prolonged exposure to subfreezing temperatures reduced or eliminated low temperature exotherms indicative of supercooling and intracellular freezing in Prunus flower buds. Apparently, the permeability of the plasma membrane to water at subfreezing temperatures and freezing rate dictate the ultimate hardiness level a plant can achieve (85).

Several physical and biochemical changes occur in plants during cold acclimation. Increased physical stability of the plasma membrane observed during acclimation may result in reduced probability of nucleation of the intracellular solution by external ice (124). Increases in unsaturation of membrane lipids increases fluidity and decreases the probability of membrane phase transition and subsequent dysfunction of membrane-bound proteins (126). Permeability of the plasma membrane to water increased during acclimation in Red-Osier dogwood (88), but was similar in acclimated and nonacclimated protoplasts isolated from rye leaves (34). The ratio of gibberellin to abscisic acid-like substances decreased during stage I acclimation in Acer leaves (63). Increases in soluble proteins, RNA, sulphydryl compounds, sugars, amino acids, and organic acids occur during acclimation of many plants (86). Water content, root hydraulic conductivity, and stomatal conductance decreased in Red-Osier dogwood during cold acclimation (54, 101, 135). As with the hypotheses of

freezing injury, none of the above physical and biochemical changes can singularly explain the resistance to freezing injury in plants.

Freezing Injury, Resistance and Cold Acclimation in Citrus

Freezing Injury

Freezing injury to citrus can be economically devastating because present and future crops are affected by a single freeze event. For example, in Texas a single freeze in Dec. 1983 reduced the production of the 1983-84 season by 70%, and extensive tree damage resulted in no production the following year (123). In Florida, damage was estimated at one half billion dollars from the 1962 freeze alone (151), and the severe freezes of Dec. 1983 and Jan. 1985 reduced commercial citrus acreage by over 80,000 ha in north-central Florida (141).

Manifestations of freezing injury in citrus range from partial defoliation and fruit abscission to death of entire trees (151, 153). Watersoaking appears as dull, dark areas on the leaf surface and is indicative of ice formation within the leaves (113, 175). However, ice formation in citrus leaves and stems is not always lethal (147, 175). Bark splitting is thought to result from large ice masses forming in the bark, creating pressure sufficient to force the tissues apart (153).

At the cellular level, Young and Mann (171) observed destruction of vacuolar, chloroplast, and mitochondrial membranes in hardened and unhardened sour orange leaves subjected to freezing at -3.3° and -6.7° C, respectively. They suggested that the nature of freezing injury in leaves was physical, caused by ice crystal growth and subsequent cellular disruption. However, they offered no explanation as to why hardened leaves undergo less cellular disruption at the same freezing temperatures than unhardened leaves, when both types of leaves contained

ice. Lower water content (167) and/or higher bound water fractions (122) in hardened leaves may reduce the amount of ice formed at a given temperature, resulting in less physical disruption than in unhardened leaves. Among citrus species, however, Anderson et al. (1) found no relationship between bound water content and freeze tolerance of leaves, and suggested that hardier species tolerate a greater amount of their water frozen than non-hardy species.

Resistance to Freezing Stress

Citrus species can survive extracellular ice formation within their tissues (147, 175), although changes in ice tolerance during acclimation remain unexplained (157). In addition, citrus avoids freezing injury by supercooling to temperatures as low as -8° C in leaves and stems (158). Citrus leaves are killed shortly after freezing occurs in the supercooled state (69, 158). The extent of supercooling in young citrus trees increased with cooling rate (164), cold hardening (61), and water stress (154), and decreased in the presence of external moisture or ice (155, 166). Also, the extent of supercooling varies with species and cultivar (157), but not in such a manner as to provide an index of interspecific or varietal differences in hardiness (158). Supercooling may not be as important a factor as ice tolerance in citrus freezing resistance because recent studies indicate that several tree species supercool only 1° to 2° C before freezing under field conditions (2, 4).

Anderson et al. (1) suggested that negative pressure potentials arise in citrus leaf cells during freeze plasmolysis, decreasing the amount of ice formed at any given temperature. This is unlikely because negative pressure potentials would have to be extremely low (< -10 MPa) to decrease the amount of ice formed significantly (86), and the only

documented measurements of negative pressure potentials are much higher (-6 kPa) (5).

Cold Acclimation

It has long been recognized that environmental conditions preceding a freeze influence the freeze survival of citrus (94). Greater freeze damage in Florida and Texas than in California under similar freeze conditions has been attributed to higher winter temperatures in Florida and Texas which reduce cold acclimation (23, 24). Several studies have demonstrated that citrus tolerates lower freezing temperatures if preconditioned for several weeks at low, nonfreezing temperatures (147, 163, 165, 173).

Generally, environmental conditions which result in inactivity or lack of growth promote cold hardiness in citrus (167). Girton (50), Fawcett (35) and Ivanov (cited in 167) were among the first to report on the influence of cool (< 13° C) temperatures on growth and cold acclimation of citrus. Seedlings exposed to alternating temperatures (warm days and cool nights) developed superior hardiness to those exposed to constant low (3° C) temperatures (96). Yelenosky (147, 151) used hardening conditions of 2 weeks at 21.1/10° C (day/night) followed by 2 weeks at 15.6/4.4° C in laboratory experiments which resulted in maximum hardiness.

Light is necessary for cold acclimation in citrus (96, 144). Length of the light period is positively correlated with growth (115, 163) but does not affect cold hardiness (96, 163) or induce bud dormancy (167). Light allows continued photosynthesis and carbohydrate accumulation during exposure to low temperature which is necessary for cold acclimation in leaves and stems (160, 166). Although

photosynthetic carbon uptake decreases during cold acclimation (169), metabolism of photosynthate also decreases (52, 160) which probably allows for net carbohydrate accumulation. Furthermore, absence or inhibited function of leaves disfavors cold acclimation (146), and starch hydrolysis cannot account for increased levels of sugars in leaves and stems (160).

Water stress increases both freezing tolerance (150) and avoidance (154) in citrus. Wilcox (138) reported that low (5° C) root temperatures induced cold hardening in citrus seedlings by reducing root hydraulic conductivity and leaf water potential. Davies et al. (28) reported that 'Orlando' tangelo trees not receiving irrigation in the fall had less leaf and fruit damage than fall irrigated trees following a radiative freeze. Conversely, Koo (71) found that trees irrigated during the fall had less leaf and fruit damage following a freeze.

In the acclimated condition, cold hardiness varies widely among citrus cultivars (157), but when unacclimated and actively growing, hardy and nonhardy types are killed at similar temperatures (151). In the acclimated condition, citrus cultivars/relatives can be ranked for hardiness in decreasing order as follows: trifoliate orange, kumquat, sour orange, mandarin, sweet orange, grapefruit, lemon, citron (157).

The hardiness of a scion cultivar is affected by the species/cultivar used as a rootstock (40, 55, 172), although hardiness differences due to rootstock are slight by comparison to cultivar differences (157). Generally, more hardy species/cultivars used as rootstocks impart more hardiness to a scion cultivar, hence the above ranking also applies to scions grafted to the species/cultivars listed.

Several biochemical and physiological changes occur in citrus during cold acclimation. Levels of soluble carbohydrates in leaves increased rapidly during the first week of acclimation in 'Valencia' orange, although levels in stems increased gradually over a 6-week period (149). The principal sugars that accumulated in 'Redblush' grapefruit were glucose, fructose, and sucrose (166). Increased levels of soluble carbohydrates may lower the freezing point of the tissue water colligatively, decrease the amount of ice formed at a given temperature, and decrease the rate of ice growth through the tissues (145, 160). All amino acids except proline, valine, and glutamic acid decreased during cold acclimation at 10° C in 'Valencia' orange (149). Proline accumulated in unacclimated, water-stressed citrus leaves (77), hence increases in proline during cold acclimation may be induced by reductions in water potential which occur during hardening (149). Proline accumulation did not correlate well with cold hardiness among citrus cultivars/species (152).

Water soluble proteins decreased in 'Redblush' grapefruit during hardening, contrary to behavior of woody deciduous plants which accumulate water soluble proteins during acclimation (166). No new proteins were identified by gel electrophoresis following cold acclimation of 'Valencia' orange trees (162). However, protein denaturation increased with freeze damage, and was greater for unhardened than hardened leaves (162). Increased levels of hydroxyproline may result from protein denaturation during cold acclimation (159).

Levels of unsaturated fatty acids and phospholipids increased during cold acclimation of citrus leaves, and the magnitude of increase

was positively correlated with the relative cold hardiness of the 3 species analyzed (97). This is consistent with the theory that increased membrane fluidity is partially responsible for increased freezing tolerance in plants (86).

Freeze Protection Methodology

Methods of freeze protection were first developed 2000 years ago, when early viticulturists protected grapevines from freezing with fires fueled by prunings and dead vines (83). Since then, many different methods of freeze protection have emerged. The concepts behind several freeze protection methods are described in the following section with reference to citrus, although nearly all of the methods can be applied to other tree crops and cropping systems.

Site Selection

Students of pomology quickly learn that site selection is one of the most important decisions a grower makes when establishing an orchard (136). Latitude, topography, and proximity of bodies of water affect the frequency and severity of freezes at a given site (9). Low-lying areas or "frost pockets" are often 5° C colder than adjacent hilltops under radiative freeze conditions, but may be slightly warmer than hilltops under advective freeze conditions (70, 132). In Florida, freeze probability and severity decrease with latitude (12, 70), and sites downwind of large lakes can be 4° C warmer than upwind sites (9). However, climatic changes can occur and render once productive sites unsuitable for growth of a particular crop, which has apparently occurred in citriculture in northern Florida (21).

Cultural Practices

Krezdorn and Martsolf (72) recently reviewed effects of cultural practices on citrus cold hardiness and orchard temperatures. They emphasized the importance of weed-free compact soil for increasing soil heat storage and conduction, proper row orientation for air drainage, maintenance of a full canopy to intercept radiant heat from the soil, and practices which keep trees in a healthy condition and maximize cold hardiness. Leyden and Rohrbaugh (80) observed higher temperatures and less freezing injury on citrus trees in sites with chemical weed control than in cultivated or sodded sites.

Orchard Heating

Orchard heating is the oldest and most reliable method of freeze protection (48, 83, 129). Several different types of fuels and heating devices have been used (83), although ordinances prohibit the use of those which produce excessive smoke and residue (129). The high costs of petroleum fuels preclude their use except for high cash value crops and in nurseries (107).

Heaters provide protection by raising the air temperature and by producing radiant heat (48). Smoke particles are not of appropriate size to retard radiant heat losses from an orchard, thus no added protection is obtained by smoke (89, 132). Radiant heat production is particularly important during windy, advective freezes when the convective component of heating is reduced (8, 137). Gerber (44) compared several types of heaters and found that radiant heat output was highest for those with large metal chimneys or mantles. Heater placement is an important factor because radiant heat decreases exponentially with distance (8, 33, 80). Absorption of radiant heat by

trees is maximized by placing heaters within rows rather than between rows (33, 137).

Pollution and expense are not the only problems associated with heating. Heaters are often difficult to light and maintain at a constant burning rate (143). Refueling heaters individually is labor intensive, and automated pipeline systems for refueling can malfunction due to clogged valves (8). Furthermore, heaters interfere with routine orchard operations during the summer (83).

Four models exist which describe theory and concepts involved in freeze protection with heaters. Martsolf (83) has reviewed the strengths and weaknesses of these orchard heating models in detail. Gerber's (43) model underestimates the heating requirement under most freeze conditions, but is fairly accurate under calm, radiative freeze conditions. Crawford's (25) model accounts for induced flow of air due to air temperature (hence buoyancy) differences inside and outside the orchard, which is lacking in Gerber's model, and predicts heat requirement within 5% of field observations. The box model of Martsolf and Panofsky is an embellishment of Crawford's model and is largely used as a research tool (83). The orchard foliage temperature model (137) is by far the most rigorous development of the orchard heating problem, but adds little to the current body of knowledge on orchard heating practices.

Wind Machines

Wind machines have been used for freeze protection since 1916 (129). Wind machines mix warmer air aloft with colder air in the orchard when a stable inversion exists, hence they are only useful under calm, radiative freeze conditions (132).

The amount of protection provided by wind machines depends primarily upon inversion strength, power of the machine, and distance from the machine (48). Leyden and Rohrbaugh (80) observed 1° to 3° C increases in air temperature over a 2.8 ha area on nights when a 4° C inversion existed. Brooks et al. (14) also reported 1° to 3° C air temperature increases over an area of 4.2 ha when inversion strength was 7° C. Turrell and Austin (130) observed that wind machines provided better protection on sites which had good air drainage than on sites with windbreaks around the perimeter. Reese and Gerber (120) concluded that on calm, clear nights wind machines can be expected to increase air temperatures 1° C over a kidney-shaped area of 4 ha.

Wind machines are sometimes combined with heaters for freeze protection, yielding results superior to those from either method used alone (84, 130). Wind machines plus 20 heaters per ha produced higher air temperatures than 40 heaters per ha alone (14).

Foam

Foam is an unstable mixture of liquid and gas which acts as an insulative blanket when applied over crops (7). Bartholic (6) found a 10° C increase in temperature under foam applied to low-growing crops. However, he found little or no elevation of leaf and air temperatures of mature citrus trees covered with foam unless heaters were used in conjunction with the foam. The additional cost and logistical difficulties associated with foam application to trees make it impractical to use (7).

Fog

Water droplets in clouds and fog are of appropriate size to cause scattering of terrestrial radiation (133). Therefore, radiant heat loss

from orchards on freeze nights is minimized in the presence of fog. Efforts to generate and maintain fog over crops for freeze protection began about 20 years ago (129). Mee and Bartholic (90) have reviewed the history and concepts associated with fog generation for freeze protection. They point out that fog not only reduces radiant heat loss from the orchard, but can also add heat through condensation and fusion of water on plant surfaces.

With mature citrus trees, fog provided about 1.5° C more protection than heaters during a -5° C freeze, and outperformed wind machines during a -8° C freeze (89). However, in tests under windy conditions, temperature increases were only 0° to 3.5° C and decreased with distance from the fog source (36). Although operating costs are very low (89), fogging systems are problematic due to the large number of emitters and purity of water required for reliable operation (90).

Flooding

Flooding orchards either before or during a freeze event can increase the temperature and heat capacity of the orchard floor (41). Heat which radiates from the soil or water surface can increase air temperatures 0.5° to 1° C (Davies personal communication). Air temperature was 0.5° to 1° C higher when the same volume of irrigation water was distributed among 3 furrows than when only 1 furrow was flooded (13). Comparable air temperature increases were obtained in citrus orchards with combinations of wind machines plus heaters, and wind machines plus flood irrigation (129).

Growth Regulator Sprays

Attempts to alter the hardiness of citrus trees by spray application of growth regulators have been largely unsuccessful (151).

Maleic hydrazide sprays applied during the fall prevented freeze injury to grapefruit seedlings during a controlled freeze at -6° C (168), but in field studies trees treated with maleic hydrazide showed similar damage to unsprayed trees 4 months following a freeze (19). Ethephon, which increased hardiness and delayed bloom of cherry buds (117), had no effect on citrus hardiness (168).

Soil Banks and Tree Wraps

Trunks of young citrus trees are protected from freezing injury by mounding soil or wrapping insulative materials around them during periods of cold weather. Following severe freezes, the entire canopy above the bank or wrap is killed, but vigorous sprouts from the protected portion of the trunk rapidly reestablish a new canopy (129).

Soil banks

In 1904 Hume (59) wrote "no method of protecting trunks of citrus trees from cold is more efficacious than banking", and with the possible exception of microsprinkler irrigation (see next section) Hume's statement remains true to this day. Hume also discussed disease and insect problems associated with soil banking, and recommended that banks be removed from trees as soon as danger of freezing is past to prevent disease damage to the trunk. Other disadvantages of banking include high labor costs and mechanical damage to trunks from construction and maintenance of the banks (68). However, soil banks continue to be used for freeze protection of young trees due to their superior insulative properties (31).

Generally, trunk temperatures under soil banks are 3° to 12° C higher than those of unprotected trees, depending on depth within the soil bank (31, 143). Rates of trunk temperature decrease during a

freeze are similar at all depths, but temperatures deeper within the bank are initially higher and start to decline later than temperatures at shallower depths (31, 143). The low thermal diffusivity and large volume of a soil bank are responsible for its superior freeze protection capability (129).

Tree wraps

Tree wraps were introduced into citriculture in the mid-1950's to circumvent the problems associated with soil banks while still providing freeze protection for young trees (80). Although tree wraps provide less protection than soil banks (67, 68, 170), they have been proven effective during freezes in Florida (121) and Texas (56). Furthermore, tree wraps provide protection from wind,radiation and rodent damage (129), and prevent trunk sprouting (121).

Early research in Texas (80, 170) demonstrated that the thickness of fiberglass insulation was positively correlated with trunk temperature, and survival of young grapefruit trees was best with the thickest wraps. These studies and others (121) showed that trunk temperatures decrease from top to bottom of wraps much as in a soil bank, but the magnitude of the temperature gradient was lower than in a soil bank.

Fucik and Hensz (39) suggested that the ratio of rates of bark to air temperature decrease was indicative of freeze protection capability of a tree wrap, and a ratio of 0.55 or less was considered adequate for freeze protection in most situations. However, trunk and air temperatures decrease at nearly the same rate with soil banks (ratio of bark and air temperature decrease is about 1.0) (31), which are superior to tree wraps with respect to freeze protection. Turrell (129) stated

that the thermal diffusivity was the primary determinant of freeze protection performance of a tree wrap, and this statement probably holds more often than the above suggestion of Fucik and Hensz.

Several different types of tree wraps are currently used, each with somewhat different insulative characteristics. A styrofoam wrap which has 2 containers of water attached to its inner surface produced higher trunk temperatures and allowed greater tree survival than other wraps in field studies (30, 67). In laboratory studies (156), this wrap maintained trunk temperatures of young 'Valencia' orange trees at 0° C when air temperatures remained at -10° C for 50 hr. Fiberglass wraps provided 0° to 3° C protection in several field studies, and the level of protection appeared to be dependent on the rate of air temperature decrease (121). Thin-walled polystyrene wraps provided very little protection, and sometimes allowed trunk temperature to fall slightly below air temperature (30, 68). The level of protection provided by other wraps was somewhere between that of the styrofoam wrap with water containers and the thin-walled polystyrene wrap (30, 67, 68). Tree wraps made of cornstalks were ineffective for freeze protection of young citrus trees (143), but have been used to prevent wind or radiation damage to trunks (129).

Sprinkler Irrigation

Sprinkler irrigation has been used successfully for freeze protection of many crops and areas of the world, from peas and beans in the Yukon territory (51) to strawberries (81) and citrus in Florida (30). Perry (109) provides a comprehensive review of field studies where sprinkling was used to protect various fruit and vegetable crops. Among the many studies in her review, there were few instances where

sprinkler irrigation was used unsuccessfully. The most notable failure of sprinkler irrigation was reported by Gerber and Hendershott (47) where mature citrus trees were killed to the ground as a result of insufficient application rates (0.25 cm hr^{-1}) during advective freeze conditions (windspeed, 2 to 5 m s^{-1}; minimum air temperature,-9° C). In their study, irrigated trees sustained more damage than unirrigated trees due to evaporative cooling and elevation of tissue killing temperatures by the presence of moisture (46).

Irrigation for freeze protection is often referred to as a "two-edged sword" because freezing of water on the plant releases heat, while evaporation extracts heat (136). The ratio of latent heats of evaporation and fusion is about 7.5, thus if 7.5 times as much water is frozen as evaporated, the temperature of the plant part will remain near ambient (48). To maintain the plant part near 0° C, an ice-water film must be constantly maintained on the surface (49). The irrigation rate required to maintain an ice-water film depends on windspeed, air temperature and humidity (20, 48, 109). Clear ice formation and icicles are field indicators of sufficient application rates (47). Trees may be damaged by excessive ice loading and limb breakage even if proper application rates are supplied under severe freeze conditions (48).

Several sprinkler irrigation models have been developed due to the need to determine appropriate application rates and maximum off times for adequate freeze protection (20, 22, 46, 111, 114). In these models the rate of heat loss due to radiation, convection and evaporation (sublimation) is set equal to the amount of heat gained by the freezing process, and the latter is divided by the heat of fusion of water to obtain the required irrigation rate. Exceptions to this are as follows:

1) the model of Chesness et al. (22) assumes that no freezing occurs, and application rate is calculated by dividing the sum of the heat loss terms by the specific heat and temperature difference between the water and the leaf; 2) the model of Phillips et al. (114) calculates the maximum time that a bud can be left unsprinkled before it drops to a critical temperature, and does not calculate or depend on irrigation rate. Predictions from the Gerber and Harrison (46) and SPAR79 (112) models have been successfully validated in the field. A BASIC computer program is available through North Carolina State University to predict irrigation rates required for freeze protection, which is essentially the SPAR79 model (110).

High- and low-volume undertree irrigation has been used to protect young and mature citrus trees (11, 15, 27, 30, 107, 108, 139). High-volume sprinklers used were the "pop-up" (27) and "impact" types (105). Low-volume undertree sprinklers are variously referred to as minisprinklers, misters, foggers, spinners, and microjets (79), but will be referred to as microsprinklers for this discussion.

High-volume irrigation increased trunk, leaf and air temperatures, and fruit pack-out in mature 'Orlando' trees in the lower third of the canopy (15, 139). However, temperatures and tree damage were similar in the upper 2/3 of the canopy. Although somewhat successful, high-volume irrigation is only feasible for protecting limited acreages due to high cost and consumption of water (15).

Observations show that microsprinkler irrigation can ameliorate the effects of less severe freezes on mature trees when relatively high irrigation rates are used (100). Microsprinkler irrigation at rates of 38 and 52 liter hr^{-1} provided marginal leaf temperature increases in the

lower portion of the canopy of 'Orlando' tangelo trees, but provided almost no fruit protection (15). Parsons et al. (107) obtained similar results with 38 and 87 liter hr^{-1} microsprinklers with mature 'Valencia' and 'Temple' orange trees during 2 relatively mild freezes.

Alternatively, microsprinkler irrigation is very effective for freeze protection of young citrus trees under a wide variety of conditions (11, 30, 104, 108). Typically, microsprinkler irrigation protects the lower 50-70 cm of a tree, and as with soil banks and tree wraps, new canopies are produced after severe freezes and trees attain heights of 1 to 2 m by the following autumn (104).

Parsons et al. (108) observed air temperature increases of 0° to 2.8° C and fog in a young tree planting irrigated with microsprinklers and suggested that partial protection was afforded by microclimate modification. However, Davies et al. (30) produced opposing evidence when they measured lower net radiation values over microspinklers that produced higher rates per unit area than those producing lower rates.

Microsprinkler irrigation at 87 liters hr^{-1} sprayed in a wedge-shaped 90° pattern protected young 'Hamlin' orange trees during one of the most severe freezes in recent history in Florida (30). In this study, it was found that tree wraps used in conjunction with microsprinklers provided 1° to 2° C more protection than microsprinklers alone. In addition, irrigated-wrapped trees had higher trunk temperatures than irrigated-unwrapped trees when irrigation was discontinued during the night. Further studies indicated that intermittent microsprinkler irrigation could be used to protect larger acreages of wrapped young citrus trees than can be accomplished with constant irrigation (32).

CHAPTER III
TRUNK TEMPERATURE, FREEZE SURVIVAL AND REGROWTH OF YOUNG CITRUS TREES AS AFFECTED BY TREE WRAPS AND MICROSPRINKLER IRRIGATION

Introduction

Thousands of young, nonbearing citrus trees have been killed by severe freezes in Florida during the last 5 years. Young trees are particularly prone to freeze damage due to their small size and vigorous growth habit. Traditionally, soil banks or tree wraps have been used for cold protection of young trees. Jackson et al. (68) compared several tree wraps with conventional soil banks and found that wrapped trunk temperatures were 0°to 1.5° C higher than those of unwrapped trunks, but 4° to 6° C lower than those of banked trunks. Although soil banks provide effective cold protection, they are labor intensive and often result in mechanical and/or disease damage to the trunk (30). In a subsequent study, wraps provided 0° to 2.5° C protection for young 'Hamlin' orange trees during several radiative freezes in Florida in 1982 (121).

Low volume, microsprinkler irrigation may provide an alternative to wraps and banks for freeze protection of young citrus trees. Davies et al. (30) successfully protected young 'Hamlin' orange trees during the advective freeze of Christmas 1983 using a combination of tree wraps and microsprinkler irrigation applied in a 90° pattern. They also showed that wraps used in conjunction with irrigation provide greater protection than either method alone. Microsprinkler irrigation without tree wraps may be less effective under advective than radiative freeze

conditions because damage was observed on trees irrigated at 38 liter hr^{-1} during the 1983 Christmas freeze (102, 103).

Because only one irrigation rate (87 liter hr^{-1}) and spray pattern (90°) were used in the study by Davies et al. (30), the objective of this research was to study the effects of different microsprinkler irrigation rates and spray patterns on trunk temperature of wrapped trees during freeze conditions, and subsequent tree survival and regrowth.

Materials and Methods

Winter 1984-85 Studies

A 0.3 ha. planting of 2-year-old 'Hamlin' orange trees (Citrus sinensis (L.) Osb.) on trifoliate orange rootstock (Poncirus trifoliata (L.) Raf.) located at Gainesville, Florida, was used in these studies. Trees were spaced 4.6 x 6.2 m and were ca. 1.5 m tall. The lower 40 cm of all trees was wrapped with 9 cm (R-11) foil-faced fiberglass insulation. Irrigation treatments were applied in an incomplete factorial combination of 4 rates (0, 38, 57, 87 liter hr^{-1}) x 2 spray patterns (90° and 360°). Microsprinklers were placed 1 m from the trees on the northwest side because winds are generally from this direction during advective freezes in Florida.

A randomized complete block design with 3 replications was used employing 3 trees per treatment per replication. Trunk temperatures of 6 of the 9 trees in each treatment were measured with copper-constantan T-type thermocouples attached to the trunk under the wrap at a height of 20 cm. Air temperature was measured at several locations throughout the planting by suspending thermocouples from the canopies of the trees at a height of about 1 m above the soil surface. Data were logged hourly

during several freezes over the winter of 1984-85. Irrigation was started when air temperature reached 0° C and discontinued when air temperature returned to 0° C. Two freezes, an advective freeze beginning on 20 Jan. 1985, and a radiative freeze beginning on 26 Jan. 1985, were selected for discussion as results from other freezes were similar.

The efficiency of each irrigation treatment (°C increase in trunk temperature per liter per hr) was calculated by subtracting the temperature of an unirrigated wrapped trunk from an irrigated wrapped trunk at the time of the lowest recorded temperature, and dividing by the irrigation rate. The lowest possible efficiency was taken as zero, although negative values could occur if the irrigated trunks were cooled by evaporation below the temperature of the unirrigated trunk.

Winter 1985-86 Studies

Studies during Dec.-Jan. 1985-86 were similar in many respects to those described in the last section. Two-year-old 'Hamlin' orange trees on sour orange (Citrus aurantium L.) rootstock planted at the same site were used to evaluate irrigation rates of 0, 12, 22, 38, and 57 liter hr^{-1}. On the basis of results of the previous winter, the 87 liter hr^{-1} rate and all 360° spray pattern treatments were not repeated. A completely randomized design was employed using 7 trees per treatment, and all trees were wrapped with foil-faced fiberglass (R-11) tree wraps. Trunk temperatures and efficiency were measured as described in the last section on 2 trees in each treatment during several freeze nights. The maximum height of live wood on all trees was measured on 14 April 1986; however, regrowth of the trees was not evaluated.

Results and Discussion

Winter 1984-85 Studies

The advective freeze on 20 Jan. 1985 was characterized by clear skies, minimum temperature near -12.0° C with durations below 0° C of 39 hr, windspeed of 2 to 6 m s^{-1} with gusts to 10 m s^{-1}, and dewpoint ranging from -8.4° to -25.6° C. The radiative freeze on 26 Jan. 1985 was characterized by clear skies, minimum temperature of -5.0° C with durations below 0° C of 12 hr, windspeed less than 1 m s^{-1} and dewpoint of -5.3° to -9.0° C.

Trunk temperatures during both types of freezes generally were higher with the 90° than 360° spray patterns at all irrigation rates, particularly when minimum air temperatures were reached (Figs. 3-1, 3-2). Trunk temperatures during the advective freeze (Fig. 3-1) were at or above -2.5° C for all irrigation treatments, while unirrigated (wrap only) trunk temperatures decreased to -8.0° C and air temperature was -12.0° C. Trunk temperatures remained above 0° C in all irrigation treatments during the radiative freeze (Fig. 3-2) while minimum temperatures were -2.0° C and -5.0° C for unirrigated trunks and air, respectively.

Fiberglass tree wraps without irrigation maintained trunk temperatures 3.0° to 4.0° C higher than air temperature under both radiative and advective freeze conditions (Figs. 3-1, 3-2). In previous studies (30, 121) fiberglass wraps provided only 1.0° to 3.0° C protection. This difference may have been due to the greater trunk diameter and/or greater rates of air temperature decrease in this study compared to past studies. Larger trunks provide greater thermal mass thansmaller ones, thus slowing the rate of decline in temperature.

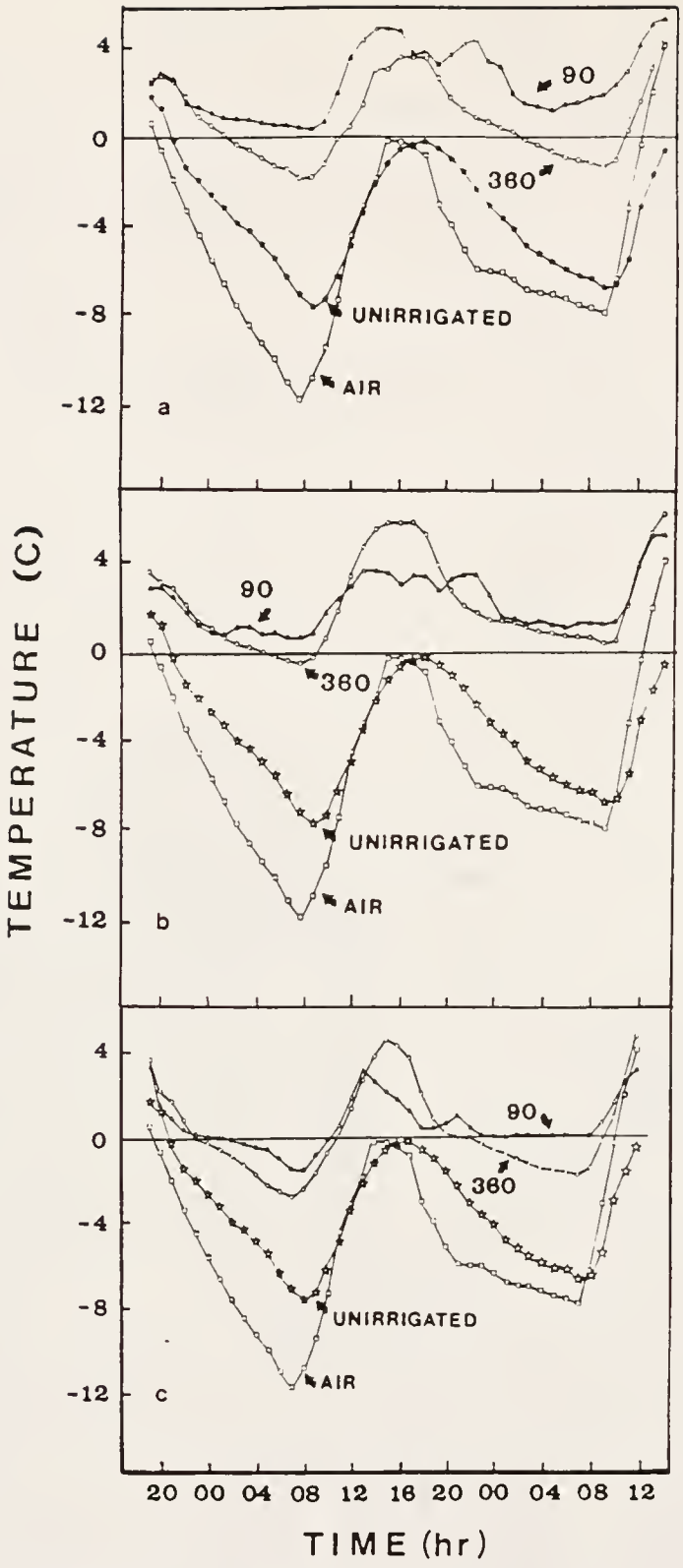


Fig. 3-1. Trunk temperatures of 2-year-old 'Hamlin' orange trees during an advective freeze of 20 Jan. 1985 as influenced by microsprinkler irrigation and tree wraps. Irrigation rates were (a) 87 liter hr^{-1}, (b), 57 liter hr^{-1} and (c), and 38 liter hr^{-1}. Spray pattern is denoted by 90 or 360. Each point is the mean of 6 measurements.

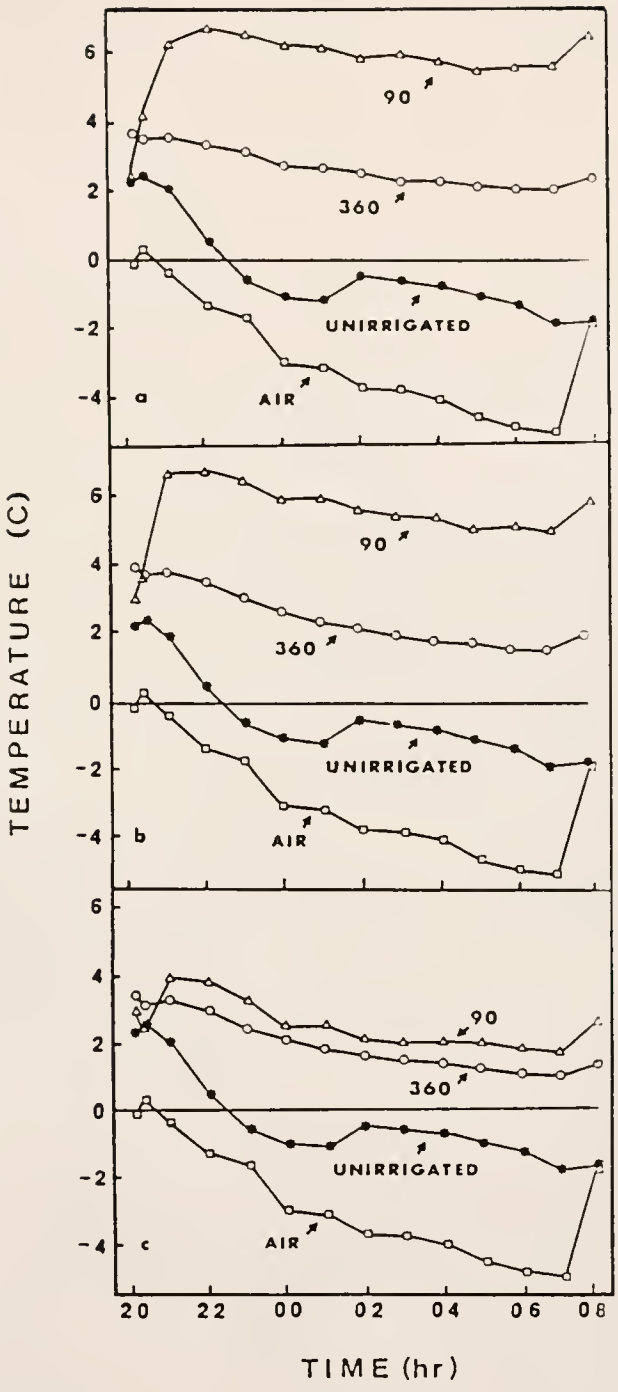


Fig. 3-2. Trunk temperatures of 2-year-old 'Hamlin' orange trees during a radiative freeze of 26 Jan. 1985 as influenced by microsprinkler irrigation and trunk wraps. Irrigation rates were (a) 87 liter hr^{-1}, (b), 57 liter hr^{-1} and (c) and 38 liter hr^{-1}. Spray pattern is denoted by 90 or 360. Each point is the mean of 6 measurements.

Also, rapid decreases in air temperature may result in larger differences between trunk and air temperatures (121).

Irrigation may have been unnecessary on 26 Jan. because wraps maintained the trunk temperatures above -2.0° C. Nevertheless, when irrigation is used, fiberglass wraps increase the surface area for water interception and ice formation around the trunk, thereby providing a buffer between the trunk and the environment should the irrigation system fail. Davies et al. (30) found that large ice masses around tree wraps maintained trunks well above air temperature for prolonged periods when irrigation was discontinued. Wraps are particularly important when using 360° emitters which produce several discrete streams of water that could miss a small tree trunk due to improper placement or windy conditions.

Trunk heating efficiency (°C increase in trunk temperature per liter per hr), decreased as irrigation rate increased, and was higher for 90° than 360° patterns at all irrigation rates (Fig. 3-3). Therefore, the 90°-38 liter hr^{-1} treatment was the most efficient pattern-rate combination. Because pumping capacity is often a limiting factor when irrigating large acreages on a freeze night, further studies are needed to determine if rates less than 38 liter hr^{-1} might maintain trunk temperatures above critical levels with equal or higher efficiency. Efficiency of lower irrigation rates is discussed in the next section.

All irrigated and wrapped trees had live scion wood as of 27 March, and only one unirrigated, wrapped tree was killed to the bud union. The height of live wood increased as irrigation rate increased for the 90° spray pattern (Table 3-1). Additionally, the dry weight and number of

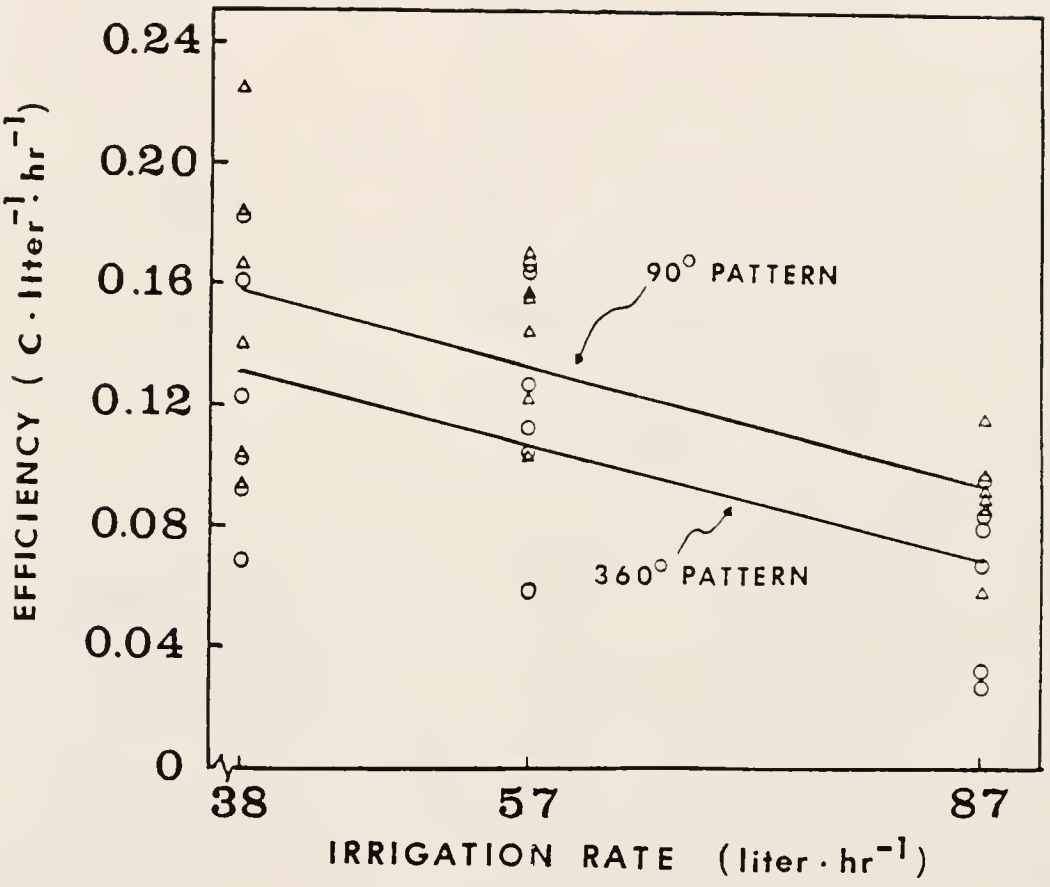


Fig. 3-3. Effect of irrigation rate on trunk heating efficiency of microsprinkler irrigation treatments for young 'Hamlin' orange trees. Efficiency was determined on 21 Jan. 1985 at 0737 hr when air temperature was lowest (-12.0° C). For 90° pattern (Δ): $y = -1.28 \times 10^{-3} x + 0.21$, $r^2 = 0.40$; for 360° pattern (o): $y = -1.26 \times 10^{-3} x + 0.18$, $r^2 = 0.33$. Slopes are not significantly different, intercepts are significantly different, 5% level.

Table 3-1. Effect of microsprinkler irrigation rate and spray pattern on height of live wood, shoot dry weight, and number of shoots per trunk on 22 April 1985.

Rate (liters hr^{-1})	Height (cm)		Dry wt. (g)		New shoots (no.)	
	Spray Pattern					
	90°	360°	90°	360°	90°	360°
0	23.4		5.3		6.9	
38	42.4	32.4	8.7	4.0	9.3	8.4
57	41.2	33.7	12.1	5.1	10.8	7.8
87	54.8	30.9	17.3	2.8	28.5	7.8
	**[z]	ns	*	ns	*	ns

[z] Regression coefficients significant at P< .01 (**), or .05 (*).

new shoots increased with irrigation rate only for the 90° pattern. This may be explained by differences in the height of water application between the 90° and 360° treatments. The 360° pattern applied water to the wrap surface at a height of about 20 cm regardless of irrigation rate. However, water from the 90° pattern tended to wet the canopy and form ice at progressively higher levels as irrigation rate increased. It was obvious from the severity of the advective freeze that the trees would die-back to wood that was protected by either wrap and/or ice because air temperatures remained below critical levels (ca -6.7° C) for several hours. Hence, it is not surprising that trees irrigated with 90° patterns had greater heights of live wood than those irrigated with the 360° pattern. Regrowth was greater in the 90° treatment probably because more wood was present; thus more adventitious buds could be initiated and undergo development.

Winter 1985-86 Studies

Two advective freezes on 25-26 Dec. 1985 and 27-28 Jan. 1986 were selected for analysis of trunk temperature because these freezes were severe enough to provide a rigorous test of the irrigation rates studied. Freeze conditions on 25-26 Dec. 1985 were characterized by minimum temperatures of about -7.0° C, windspeeds decreasing throughout the night from 3 to < 1 m s^{-1}, and dewpoints of about -10° C. Conditions on 27-28 Jan. 1986 were characterized by minimum temperatures of about -7.0 °C, windspeeds of 1 to 4 m s^{-1}, and dewpoints of about -14° C. In addition to the 2 advective freezes, data from 3 radiative freezes on 22 Dec. 1985, 27 Dec. 1985, and 29 Jan. 1986 were used to evaluate trunk heating efficiency, when minimum air temperatures of

-3.2°, -4.0°, and -2.5° C, respectively, occurred under calm, high dewpoint conditions.

Trunk temperatures during advective freeze conditions increased with irrigation rate up to 38 liters hr^{-1}, but were similar for the 38 and 57 liter hr^{-1} treatments (Fig. 3-4). Trunk temperatures for the 38 and 57 liter hr^{-1} irrigation rates were maintained well above 0° C, while those for the 12 and 22 liter hr^{-1} treatments decreased to about -1.0° and -3.0° C, respectively, on both dates. Unirrigated wrapped trunks had temperatures just slightly below those for the 12 liter hr^{-1} rate, hence, this irrigation rate provided little additional trunk heating compared to the other rates. The relatively poor performance of the 12 liter hr^{-1} rate cannot be entirely attributed to the irrigation rate per se, as droplet size was noticeably different for this treatment. Rather than the raindrop-sized droplets of higher irrigation rates, the 12 liter hr^{-1} emitters produced a fine mist, causing large amounts of opaque ice to form on the wrap and lower limbs of the trees. Opaque ice formation is indicative of water freezing before it reaches the tree (46), which could be expected with mist-sized droplets that cool rapidly as they travel through the air due to their high surface to volume ratio and low heat capacity (20). Hence, small droplet size may have been partially responsible for the poor protection afforded by the 12 liter hr^{-1} rate.

Despite differences in trunk temperature due to irrigation rate, height of live wood was not significantly related (linearly or quadratically) to irrigation rate (Table 3-2). This is contrary to results of 1984-85 studies, but may be explained by the less severe freeze conditions during the 1985-86 winter causing less trunk damage in

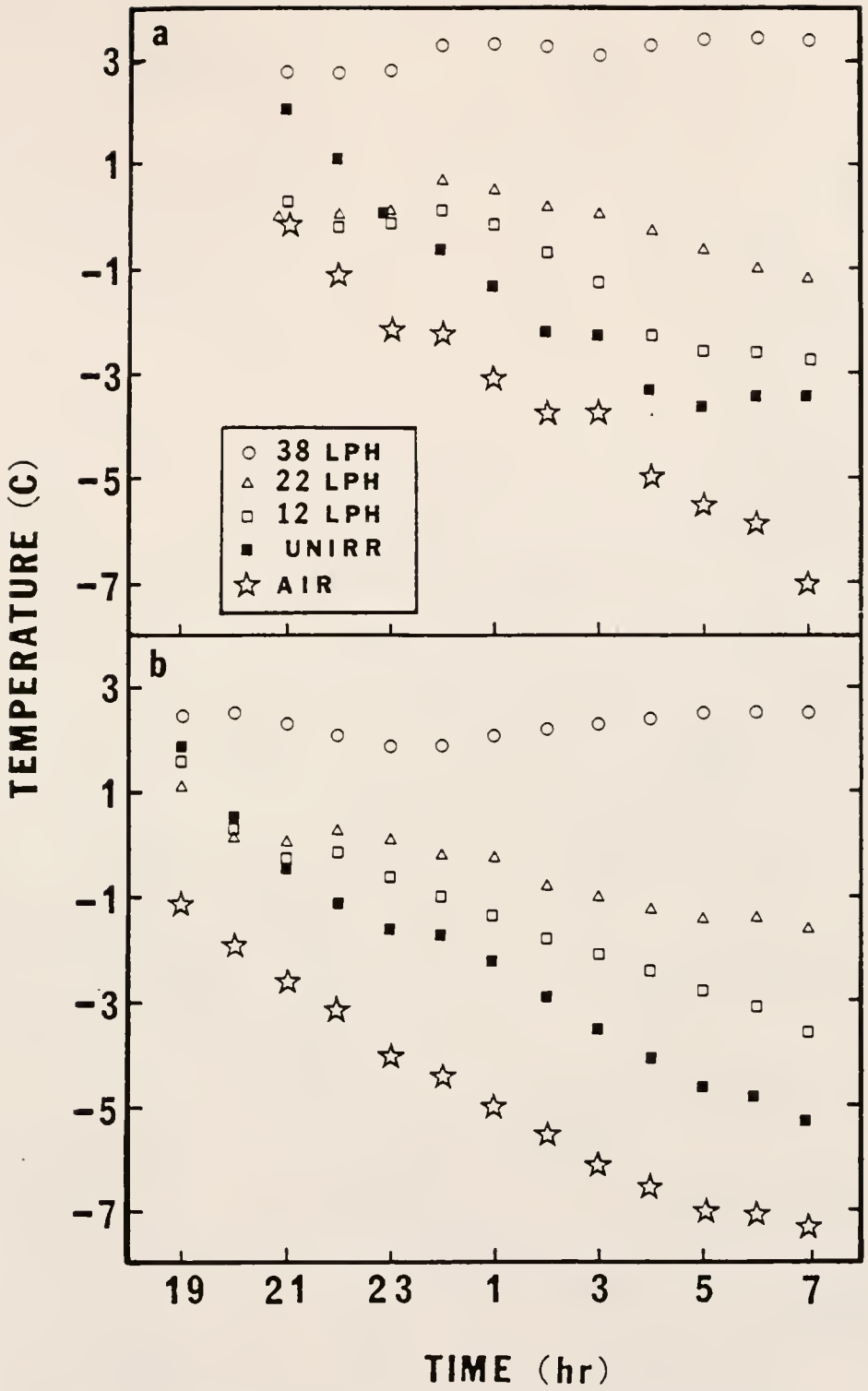


Fig. 3-4. Trunk temperatures of 2-year-old 'Hamlin' orange trees and air temperatures during advective freezes of 25-26 Dec. 1985 (a), and 27-28 Jan. 1986 (b) for unirrigated (UNIRR), 12, 22 and 38 liter hr^{-1} (LPH) microsprinkler irrigation treatments. Trunk temperatures in the 57 liter hr^{-1} treatment were similar to those for the 38 liter hr^{-1} treatment, hence are not shown. Trunk temperatures were measured at the 20-cm height underneath fiberglass tree wraps on 2 trees in each treatment.

Table 3-2. Height of live wood of young 'Hamlin' orange trees on 14 April 1986 as influenced by microsprinkler irrigation rate during several freezes in Dec.-Jan. 1985-86.

Rate (liters hr^{-1})	Height of live wood (cm)
0	54.7 ± 20.1[z]
12	35.9 ± 12.5
22	56.9 ± 15.6
38	46.1 ± 15.6
57	57.3 ± 12.8

[z] Values of height of live wood are means ± SD. Linear and quadratic regression coefficients were not significant, $P < 0.05$. n=7.

general, particularly for unirrigated trees. However, trees in the 12 liter hr^{-1} treatment were noticeably smaller than all other trees, and the visually greater canopy damage may have resulted from insufficient water application under windy conditions, i.e., evaporative cooling.

Trunk heating efficiency was calculated for 5 different freeze nights and data were fitted most closely by a quadratic equation (Fig. 3-5). Setting the derivative of the equation equal to 0, the relative maximum point on the curve was obtained which corresponded to the value of the most efficient irrigation rate (position of the star in Fig. 3-5). Similar to the winter 1984-85 data, trunk heating efficiency was highest for the 38 liter hr^{-1} irrigation rate (with a 90° spray pattern) under the widely varying freeze conditions encountered on 5 nights during the winter of 1985-86 (Table 3-3). This is rather fortunate because most citrus growers in Florida that have microsprinkler irrigation systems use the 38 liter hr^{-1} rate (Davies, personal communication), and trunk heating efficiency could be maximized by simply changing from 360° to 90° spray patterns.

Conclusions

The 90° spray pattern was superior to the 360° spray pattern with respect to maintenance of trunk temperature during freeze conditions, and survival and regrowth of the trees the following spring. A microsprinkler irrigation rate of 38 liter hr^{-1} was most efficient for maintaining trunks of wrapped young citrus trees above damaging temperatures under a variety of freeze conditions. Twice as much acreage can be protected using a 38 liter hr^{-1} than a 87 liter hr^{-1} microsprinkler with a 90° pattern given the same pumping capacity. Use of irrigation rates $<$ 38 liter hr^{-1} with 90° spray patterns can provide

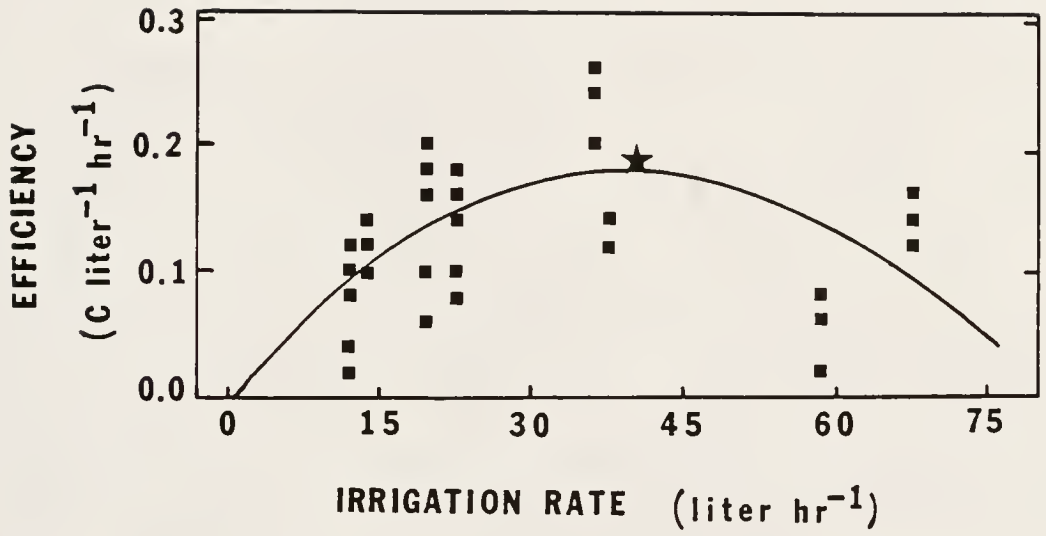


Fig. 3-5. Trunk heating efficiency as a function of irrigation rate for 5 freezes during Dec.-Jan. 1985-86. Solid line is a quadratic regression fitted through the data; the star denotes the relative maximum on the fitted curve. Each point is a single determination.

Table 3-3. Dates of freezes, minimum air temperatures, most efficient irrigation rates, and coefficients of determination from quadratic regressions of trunk heating efficiency vs. irrigation rate during Dec.-Jan. 1985-86.

Date	Minimum air temperature[z] (°C)	Most efficient irrigation rate[y] (liters hr^{-1})	r^2
Dec. 22	-3.2	38.5	0.76
Dec. 26	-7.0	41.0	0.48
Dec. 27	-4.0	40.4	0.51
Jan. 28	-7.3	38.6	0.54
Jan. 29	-2.5	40.6	0.32

[z] Air temperatures are means of 7 measurements.
[y] Most efficient irrigation rate was calculated by setting the derivative of the quadratic regression equations equal to zero and solving for the relative maxima for each date.

1° to 4° C additional trunk protection over tree wraps alone and allow even larger acreages to be protected on any given night. However, height of live wood and regrowth of trees may be marginally greater using higher irrigation rates.

CHAPTER IV
MICROCLIMATE OF YOUNG CITRUS TREES PROTECTED BY MICROSPRINKLER IRRIGATION DURING FREEZE CONDITIONS

Introduction

Methods of freeze protection that use water include flood irrigation, fog generation and sprinkler irrigation, and each influences the microclimate of the orchard. Flooding an orchard during a freeze can increase soil and air temperatures and upward radiant heat flux from the orchard floor (13, 41), thereby increasing temperatures of the trees. Pre-freeze irrigation by either flooding or sprinkling can have similar effects, but does not present the problem of standing water in the orchard (41). Fog retards the loss of infrared radiation from the orchard and raises the dewpoint, which can prevent tree temperatures from decreasing to damaging levels (89). Therefore, flood irrigation and fog generation affect temperatures of trees primarily by modifying the microclimate of the orchard.

Alternatively, sprinkler irrigation provides protection primarily through direct transfer of latent heat from the ice-water mixture that coats the tree (20, 46, 109). However, microclimate modification by high-volume sprinkler irrigation has been observed for mature citrus trees (15, 27, 108, 139). Leaf and air temperatures were 0° to 3° C higher for irrigated than unirrigated 'Orlando' tangelo trees (27, 139) and protection varied with position in the canopy and freeze conditions. Parsons et al. (107) reported 0° to 1° C differences in air temperature

between irrigated and unirrigated mature citrus canopies using low-volume microsprinkler irrigation. Fog or mist generation by microsprinklers may occur under high dewpoint conditions and is thought to decrease radiant heat loss from the trees and soil surface (108). However, canopy temperatures at the 2 and 3 m height of irrigated citrus trees were similar to those of unirrigated trees, despite the presence of fog or mist in the irrigated block (139). Preliminary studies indicated that net radiation above young citrus trees was about 8 W m^{-2} more negative with high irrigation rates than low rates, but values for unirrigated trees were not reported (30).

The effect of microsprinklers on microclimate and subsequent freeze damage of young citrus trees is unclear. The objective of this research was to determine the effect of microsprinkler irrigation on air temperature, dewpoint, net radiation and soil temperature around young citrus trees under various freeze conditions.

Materials and Methods

Plant Material, Freezes and Treatments

A 0.3-ha planting of 126 2-year-old 'Hamlin' orange (Citrus sinensis (L.) Osb) trees on either trifoliate orange (Poncirus trifoliata (L.) Raf.) or sour orange (Citrus aurantium L.) rootstock was used for all experiments. Trees were spaced 4.6 x 6.2 m and were 0.5 to 1.5 m in height. The lower 40 cm of all trees was wrapped with 9 cm (R-11) foil-faced fiberglass insulation. Microsprinklers were placed 1 m from the trees on the northwest side because winds are generally from this direction during advective freezes in Florida.

Microclimate measurements during 6 freezes which had widely variable meteorological conditions were chosen for analysis of treatment

effects. The advective freeze of 20-22 Jan. 1985 was characterized by minimum temperature near -12.0° C with durations below 0° C of 39 hr, windspeed of 2 to 6 m s^{-1} with gusts to 10 m s^{-1}, and dewpoint ranging from -8.4° to -25.6° C. The radiative freeze on 26-27 Jan. 1985 was characterized by minimum temperature of -5.0° C, windspeed < 1 m s^{-1}, and dewpoint of -5.3° to -9.0° C. Freeze conditions on 25-26 Dec. 1985 were characterized by minimum temperature of -7.0° C, windspeed of 1 to 3 m s^{-1}, and dewpoint of about -10.0° C. Minimum temperature on 27-28 Jan. 1986 was about -7.0° C, windspeed was 1 to 4 m s^{-1}, and dewpoint was about -14.0° C. On 26-27 Dec. 1985, minimum temperature was about -4.0° C, windspeed was 0 to 2 m s^{-1}, and dewpoint averaged -7.0° C. Minimum temperature on 11-12 Jan. 1987 was -1.5° C, windspeed was 1 to 3 m s^{-1}, and dewpoint was about -4.0° C.

In Jan. 1985, treatments were applied in a factorial combination of 3 irrigation rates (38, 57, and 87 liters hr^{-1}) x 2 spray patterns (90° and 360°), plus an unirrigated control. Four irrigation rates (12, 22, 38, and 57 liters hr^{-1}) were used with only the 90° spray pattern in Dec.-Jan. 1985-86, plus an unirrigated control. In Jan. 1987, only a 90° pattern-38 liter hr^{-1} rate irrigation treatment and an unirrigated control were used.

Microclimate Measurements

Microclimate around young trees was measured during the freezes described above for irrigated and unirrigated trees. Air and soil temperature, dewpoint, and net radiation data were recorded hourly during the freezes in Jan. 1985. Soil temperature measurements were repeated during the 3 freezes in Dec.-Jan. 1985-86 because measurements from the previous year were speculative. Net radiation measurements

were repeated on 11-12 Jan. 1987 to confirm results from 1985. Observations on fog and mist generation by microsprinklers were made on all dates. Relative humidity and temperature measurements were made on all dates inside and outside the planting with a sling psychrometer.

Air temperature was measured with copper-constantan thermocouples in the canopy of one tree in each treatment at a height of 1 m. Relative humidity was measured with humidity sensors (Viasala instruments, Woburn, Mass.) at the same location as air temperature for one tree in each treatment, and dewpoint was calculated from simultaneous measurements of air temperature and relative humidity. Net radiation was measured with Fritschen-type net radiometers placed at a height of 0.8 m and centered directly over the water spray, between the tree and the microsprinkler. Preliminary experiments indicated that at a height of 0.8 m, net radiometers were sensitive enough to measure differences in upward radiant flux of about 5-10 W m^{-2} from an area of about 2.8 m^2 (data not shown). One net radiometer per treatment was used during winters of 1984-85 and 1985-86, but in 1986-87, 4 net radiometers per treatment were used. Soil temperature was measured with thermocouples placed approximately 1 cm below the soil surface next to the trunk of 1 tree in each treatment. This location was chosen because it was suspected that soil temperature could influence trunk temperature above the soil surface by conduction of heat vertically along the trunk.

Results and Discussion

Microsprinkler irrigation rate did not affect air temperature, dewpoint or net radiation of the trees within either the 90° or 360° spray pattern during the winter of 1984-85 (data not shown). Hence, data were classified as either irrigated-90°, irrigated-360° or

unirrigated to simplify discussion of these variables. Soil temperature data are discussed for the 90° pattern only, because thermocouple placement for the 360° spray pattern treatments caused spurious measurements.

Air Temperature

Air temperature in the tree canopy was similar for irrigated-90°, irrigated-360° and unirrigated treatments during severe advective and radiative freezes (Fig. 4-1). Furthermore, air temperatures for all trees were typically within 0.5° C of those outside the research plot under both types of freeze conditions (data not shown). Temperature differences between irrigated 90° and unirrigated treatments approached 1.0° C under radiative conditions for a 3-hr period in the middle of the night on 26-27 Jan. 1985. This may have been attributable to heat released by the irrigation water, but was more likely due to random variation in air temperatures which is frequently observed on radiative nights. Parsons et al. (108) observed consistent increases in air temperature of 0.5° to 1.5° C for irrigated young trees, although their microsprinklers were more closely spaced and freeze conditions were less severe than in this study.

Dewpoint

Variations in dewpoint were typically less than 1° C among irrigated-90°, irrigated-360°, and unirrigated treatments under advective and radiative freeze conditions (Fig. 4-2). As with air temperature, there was a 3-hr period in the middle of the radiative freeze night where values were higher for the irrigated-90° than unirrigated trees (Fig. 4-2b). However, this may be a mathematical artifact because air temperature was used to calculate dewpoint.

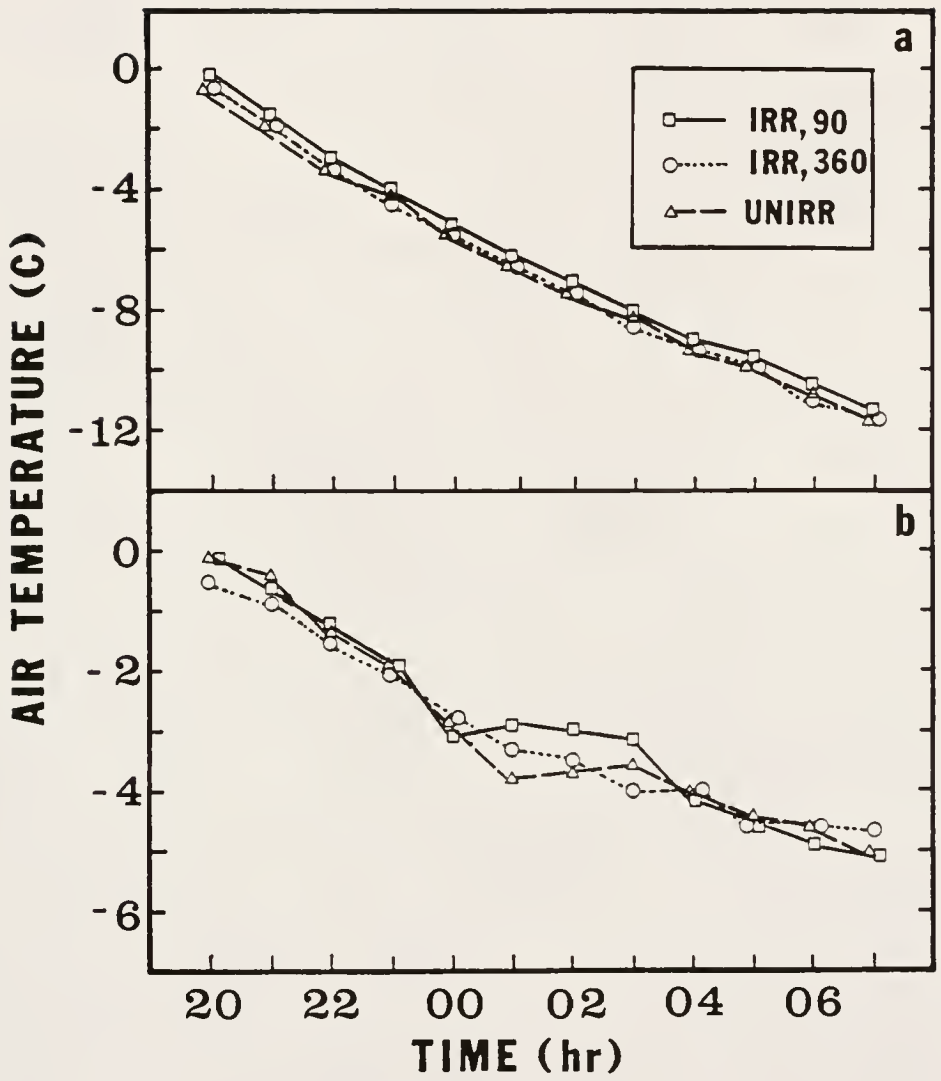


Fig. 4-1. Air temperature in the canopy of 2-year-old 'Hamlin' orange trees during a severe advective freeze on 20-21 Jan. 1985 (a) and a radiative freeze on 26-27 Jan. 1985 (b). Points are means of 3 values for the irrigated-90° (IRR,90) and irrigated-360° (IRR,360) treatments, and single values for unirrigated (UNIRR) treatments.

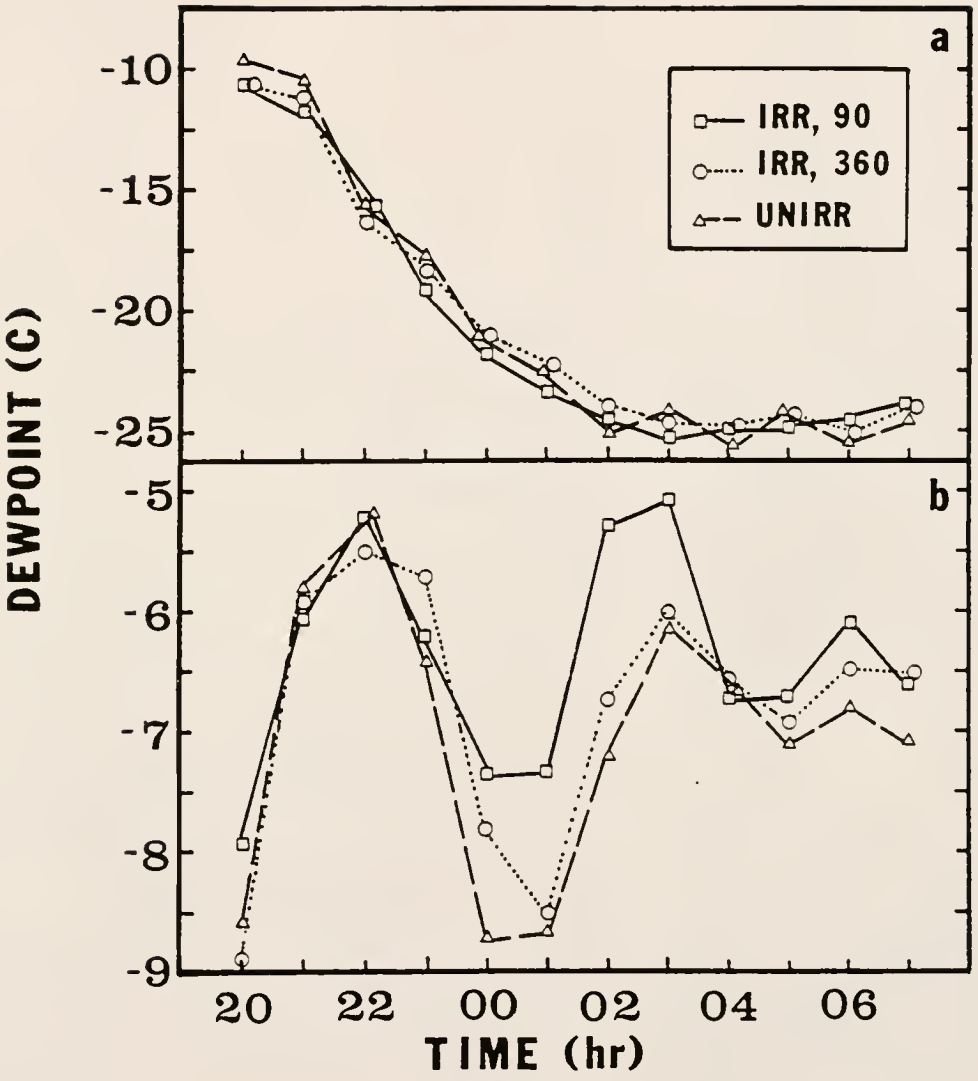


Fig. 4-2. Dewpoint temperature in the canopy of 2-year-old 'Hamlin' orange trees during a severe advective freeze on 20-21 Jan. 1985 (a) and a radiative freeze on 26-27 Jan. 1985 (b). Points are means of 3 values for the irrigated-90° (IRR,90) and irrigated-360° (IRR,360) treatments, and single values for unirrigated (UNIRR) treatments. Dewpoint was calculated using simulataneous air temperature and relative humidity measurements.

Mist often was observed over irrigated trees only during calm conditions when dewpoint was close to air temperature, similar to the observations of Parsons et al. (108). However, humidity measurements made with a sling psychrometer above unirrigated trees were similar to those outside the research plot (typically 60-100%), indicating that microclimate around unirrigated trees within the plot was not influenced by mist from neighboring irrigated trees.

Net Radiation Net radiation was 10 to 20 W m^{-2} more negative over irrigated than unirrigated treatments under advective freeze conditions (Fig. 4-3a). Higher net radiation values over unirrigated than irrigated trees were observed again during a less severe freeze on 21-22 Jan. 1985 (data not shown). Net radiation values outside the planting were comparable to values for unirrigated trees inside the planting. Hence, the increase in outgoing radiation from the irrigated treatments was localized, and probably caused by the presence of the relatively warm irrigation water. If irrigation were favorably modifying the microclimate of the trees, one would expect net radiation to be less negative over irrigated trees, but the opposite situation is seen (Fig. 4-3a).

No differences in net radiation occurred between irrigated and unirrigated treatments or among irrigated treatments under radiative freeze conditions (Fig. 4-3b). Net radiation was measured above irrigated (38 liter hr^{-1}-90° microsprinklers) and unirrigated trees during a mild, radiative freeze on 11-12 Jan. 1987 to verify results from 1985. Again, net radiation was found to be similar for irrigated and unirrigated trees (Fig. 4-4), consistent with data in Fig. 4-3b. Reasons for the lack of differences in net radiation between irrigated

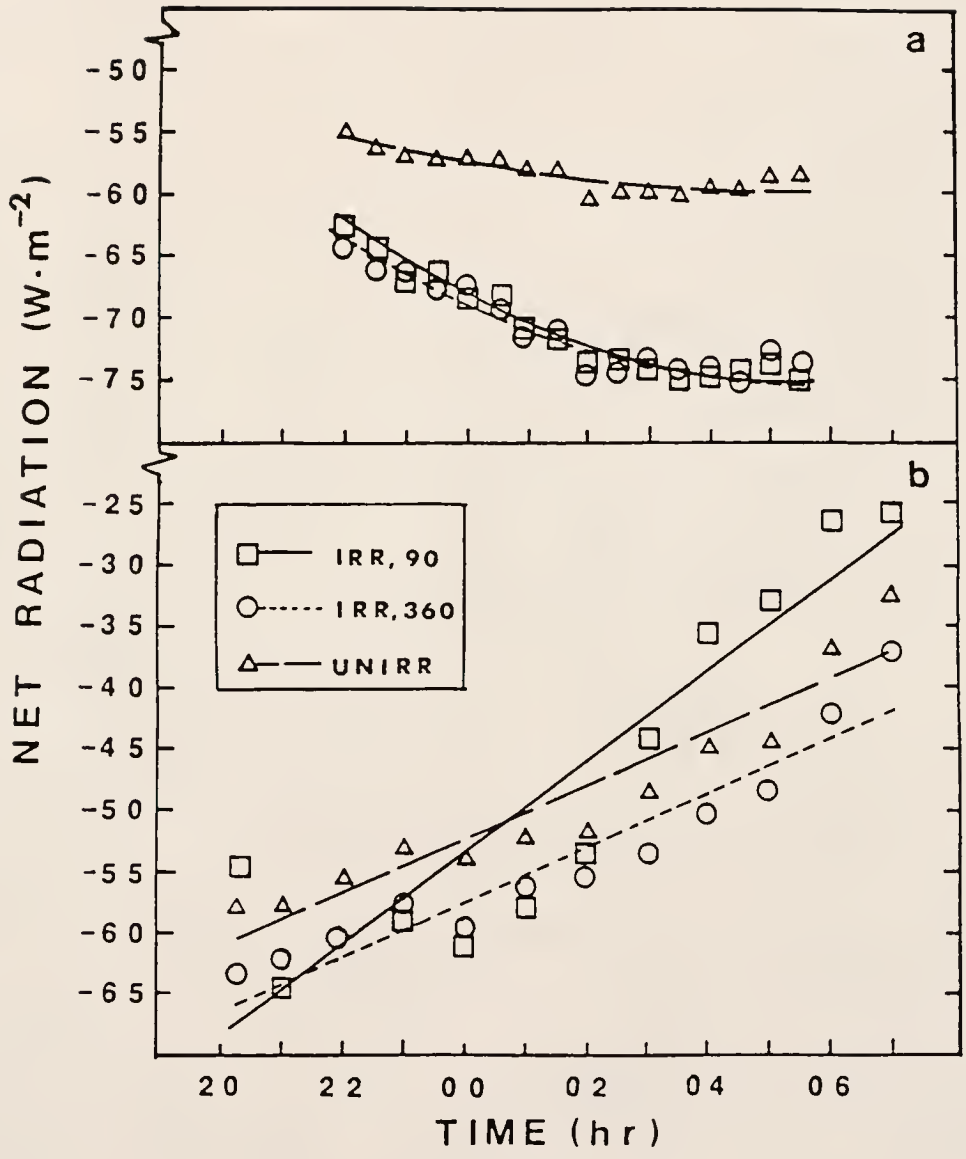


Fig. 4-3. Net radiation above 2-year-old 'Hamlin' orange trees during a severe advective freeze on 20-21 Jan. 1985 (a) and a radiative freeze on 26-27 Jan. 1985 (b). Points are means of 3 values for the irrigated-90° (IRR,90) and irrigated-360° (IRR,360) treatments, and single values for unirrigated (UNIRR) treatments.

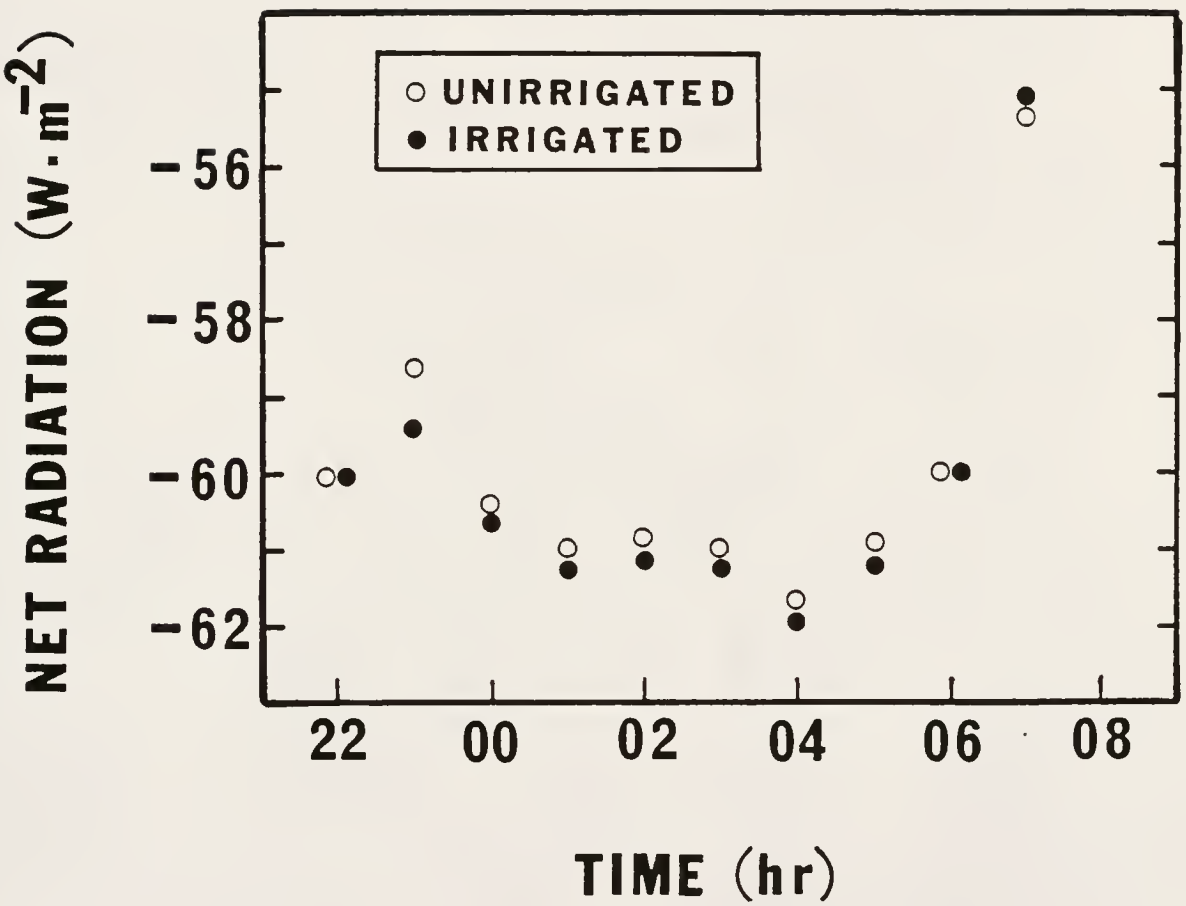


Fig. 4-4. Net radiation above 2-year-old 'Hamlin' orange trees during a radiative freeze on 11-12 Jan. 1987. Points are means of 4 values for irrigated and unirrigated treatments.

and unirrigated trees under radiative conditions are unclear. Variability in incoming radiation under calm conditions may have masked any slight differences in upward radiant flux on both occassions.

Davies et al. (30) measured net radiation values of -61.3 and -53.1 W m^{-2} above trees irrigated with 90°-87 liters hr^{-1} and 360°-38 liters hr^{-1} microsprinklers, respectively, under radiative conditions. Their results could be explained by the presence of greater quantities of 10° to 15° C irrigation water underneath net radiometers for the higher than the lower irrigation rate. However, it is unclear why differences between 90° and 360° spray patterns were not detected under radiative conditions in this study. Possibly, different net radiometer placement (1.5 m for Davies et al. (30) and 0.8 m in this study) was responsible for the conflicting results.

Soil Temperature

Soil temperature generally was highest for the 38 liter hr^{-1} rate, intermediate for unirrigated trees, and lowest for the 12 liter hr^{-1} rate during 3 freezes in Dec.-Jan. 1985-86 (Fig. 4-5). The soil temperatures for the 22 and 57 liter hr^{-1} treatments were very similar to those for the 12 and 38 liters hr^{-1} treatments, respectively. The mist-sized droplets in the 12 liter hr^{-1} treatment probably cooled to a greater extent as they traveled through air than larger droplets in other treatments (46) and consequently reduced soil temperature below that for unirrigated trees. However, droplet size was comparable for 22 and 38 liters hr^{-1} microsprinklers, and the reduced soil temperature for the former treatment cannot be explained by greater droplet cooling.

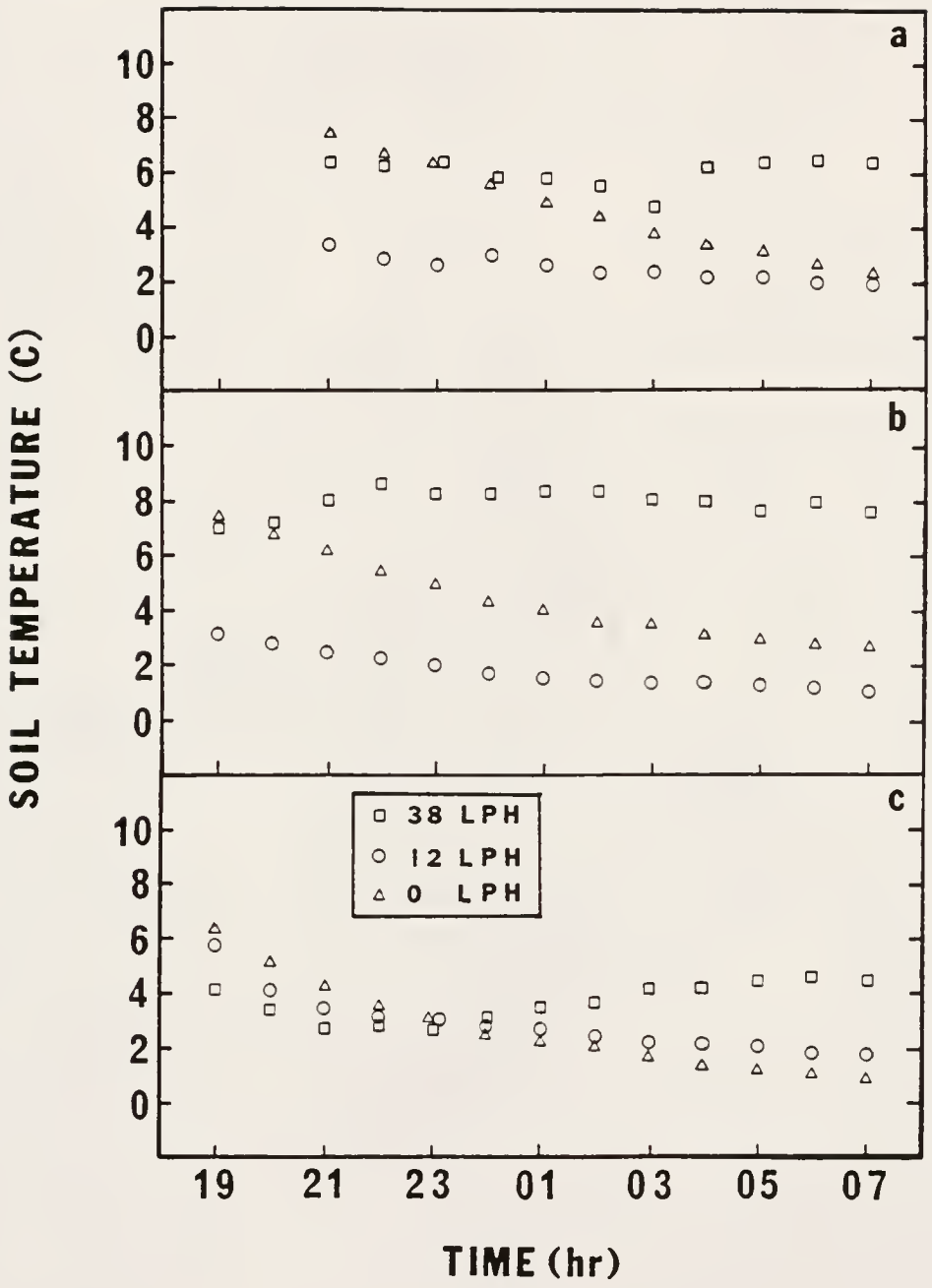


Fig. 4-5. Soil temperature measured 1 cm below the surface and next to trunks of 2-year-old 'Hamlin' orange trees during freezes on 25-26 Dec. 1985 (a), 26-27 Dec. 1985 (b), and 27-28 Jan. 1986 (c). Points are single values for the unirrigated (0 LPH), 12 (12 LPH) and 38 liter hr^{-1} (38 LPH) treatments.

Conclusions

Microsprinkler irrigation does not appear to change the microclimate of a young tree in the same way as reported for mature trees (15, 107). Mature trees have much greater canopy volume than young trees, hence a greater capacity to decrease radiation loses and reduce windspeeds within the canopy, and retain heat released from irrigation water. Irrigation may, under certain conditions, increase the long-wave radiant flux from the vicinity of a young tree, but these effects appear to be localized and do not affect air temperatures. Irrigation rates > 38 liters hr^{-1} elevated soil temperature 2° to 6° C, while lower irrigation rates reduced soil temperature 2° to 4° C with respect to the unirrigated condition. Therefore, it is possible that heat conducted along the trunk from the soil is partially responsible for elevation of trunk temperatures of wrapped young citrus trees irrigated with 38 liter hr^{-1} (or higher rate) microsprinklers. This possibility is investigated in Chapter VII.

CHAPTER V
TRUNK TEMPERATURE, LIGHT INTENSITY AND SPROUTING OF WRAPPED AND UNWRAPPED YOUNG 'HAMLIN' ORANGE TREES FOLLOWING A FREEZE

Introduction

Tree wraps not only provide freeze protection for young citrus trees during the winter (68, 121, 156) but also influence trunk sprouting in the spring. Trunk sprouting on freeze-damaged trees may be beneficial or deleterious, depending on the degree of injury sustained by the canopy. Following less severe freezes, ample canopy wood may survive and produce new shoots. In this case trunk sprouting would be undesirable, occurring at the expense of growth of scaffold limbs. However, severe freezes may kill a young tree nearly to the bud union, and the development of trunk sprouts would be necessary for the reestablishment of the tree canopy. In either case, absence or presence of a tree wrap and the type of wrap become important factors in the regrowth and proper training of a young citrus tree.

Sprout inhibition by wraps may be a result of a physical barrier imposed by a close fitting wrap, and/or modification of the environmental factors influencing sprout growth such as temperature and light intensity. Shoot initiation and growth are strongly temperature dependent in citrus (23, 35, 119, 163), and light is necessary for shoots to become autotrophic and continue growth once initiated. The temperature and light regimes underneath wraps have not been studied in the early spring when sprout initiation and development occur. Moreover, the influence of various trunk wraps on trunk sprouting has

not been critically examined in citrus. The objective of this study was to monitor the temperature and light environment of young citrus tree trunks underneath various wraps during early spring, and to examine the relationship between these environmental factors and trunk sprouting in freeze damaged trees.

Materials and Methods

Two-year-old 'Hamlin' orange trees (Citrus sinensis (L.) Osb.) on trifoliate orange rootstock (Poncirus trifoliata (L.) Raf.) located at Gainesville, Florida were used in this study. These trees were protected from severe freezes during the 1984-85 winter with fiberglass tree wraps and microsprinkler irrigation, but were killed back to a height of about 60 cm. On 26 Feb. 1985, fiberglass wraps were removed and 6 wrap treatments applied to 36 trees in a randomized complete block design as follows: unwrapped (UW), fiberglass (FG), styrofoam (SF), styrofoam modified to exclude light (MSF), white polystyrene (WP) and charcoal polystyrene (CP). These treatments were chosen to provide separation of light and temperature effects on trunk sprouting. The wraps covered the lower 40 cm of the trunk, of which about 35 cm was scion wood. Most trees had sprouts above the wrapped portion of the trunk at this time, but no sprouts were observed on the lower 40 cm.

Trunk temperature was measured with copper-constantan thermocouples taped to the trunk at a 20-cm height. Air temperatures were measured with thermocouples suspended on canopy wood 1 m above the ground. Photosynthetic photon flux (PPF) was measured with Li-Cor quantum sensors taped to the trunk near the thermocouples. Due to a shortage of quantum sensors, PPF could only be measured on 3 of the 6 treatments during any particular day. Therefore, temperature and PPF measurements

were made over a 20 day period in March, 1985, the quantum sensors being moved among treatments on different days. Temperatures were measured hourly and PPF at 15 min. intervals.

Sprouts from the lower 40 cm of the trunks were removed and counted on 13 May 1985, after treatments had been in place for 76 days, and placed in an oven at 80° C for 24 hr for dry weight determination. Temperature, sprout number and dry weight data were analyzed for treatment effects using analysis of variance and Duncan's multiple range test. Although PPF data could not be analyzed statistically, data for any particular wrap treatment on different days with similar sky conditions were comparable.

Results and Discussion

Generally, trunk temperatures under WP and CP wraps were highest and those under SF and MSF wraps lowest during the daylight hours, with FG, UW and air temperatures intermediate (Fig. 5-1). However, in the afternoon on cloudy days, all wrapped trunk temperatures were generally higher than the air temperature, but differences among wrap treatments were small and varied from hour-to-hour. In mid-afternoon on sunny days, differences in trunk temperatures between WP and MSF treatments approached 17° C, and temperatures under WP wraps reached 41° C. In addition, temperatures remained above 38° C under WP wraps for 3 to 4 hr, while temperatures under MSF wraps generally remained below 29° C. During the night, temperatures under the SF and MSF wraps were highest, lowest for WP, CP, UW and air, and intermediate for FG. By sunrise , the temperatures under the MSF wraps were significantly higher (0.5° to 1.0° C) than all other treatments. This was probably a result of the covering of black tape used to exclude light which made the wrap

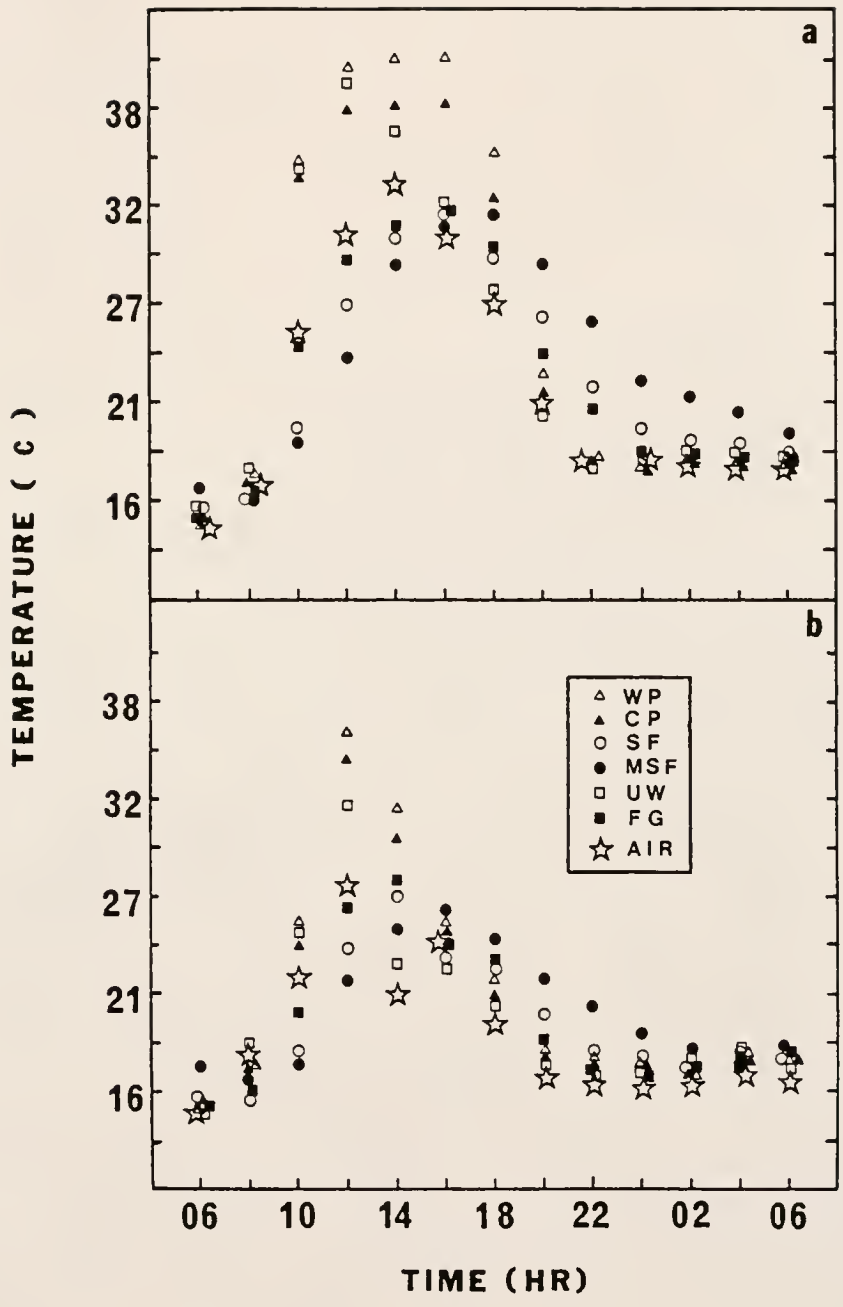


Fig. 5-1. Diurnal trunk temperatures of young 'Hamlin' orange trees underneath various trunk wraps during a typical sunny day (a) and a cloudy day (b) in March, 1985. Each point is the mean of 6 measurements. Abbreviations are as follows: white polystyrene (WP), charcoal polystyrene (CP), styrofoam (SF), modified styrofoam (MSF), unwrapped (UW), and fiberglass (FG).

airtight, and thus a better insulator than the SF wrap which was ventilated. Although statistically different, it is questionable whether a 0.5° to 1.0° C difference in nighttime temperature is of biological significance to a young tree with respect to trunk sprouting.

The range of trunk temperature encountered in this experiment (16° - 41° C) was above the 13° C threshold which qualitatively controls budbreak (119, 163) and below the 50° C threshold which can cause tissue damage in citrus (62, 119). Prolonged periods of relatively high trunk temperature as observed for some wraps in this study might adversely affect cambial activity and ultimately the growth of a young tree. Alternatively, such wraps may induce earlier resumption of cambial activity in the spring by raising trunk temperature to levels favorable for growth. Further studies on the influence of tree wraps on growth of young trees are warranted due to the widespread use of wraps for protection from freeze, herbicide, and fertilizer damage.

Photosynthetic photon flux varied from ambient on unwrapped trunks to undetectable levels on trunks of FG and CP treatments. The WP wrap allowed the most PPF transmission (9-13% of ambient) followed by SF (4-9% of ambient) and then MSF (less than 0.1% of ambient) (Fig. 5-2). In the UW, WP and SF treatments, PPF was well above the reported light compensation point for citrus (73) which is about 1-2% of full sunlight.

Unwrapped trunks had highest sprout numbers and dry weights of all treatments (Table 5-1). Number of sprouts in the WP treatment was statistically similar to the UW treatment, but sprouts in the WP treatment were deformed and had lower dry weights than those in UW treatment. Apparently this was due to the physical limitations on sprout growth imposed by the wrap. All other treatments had

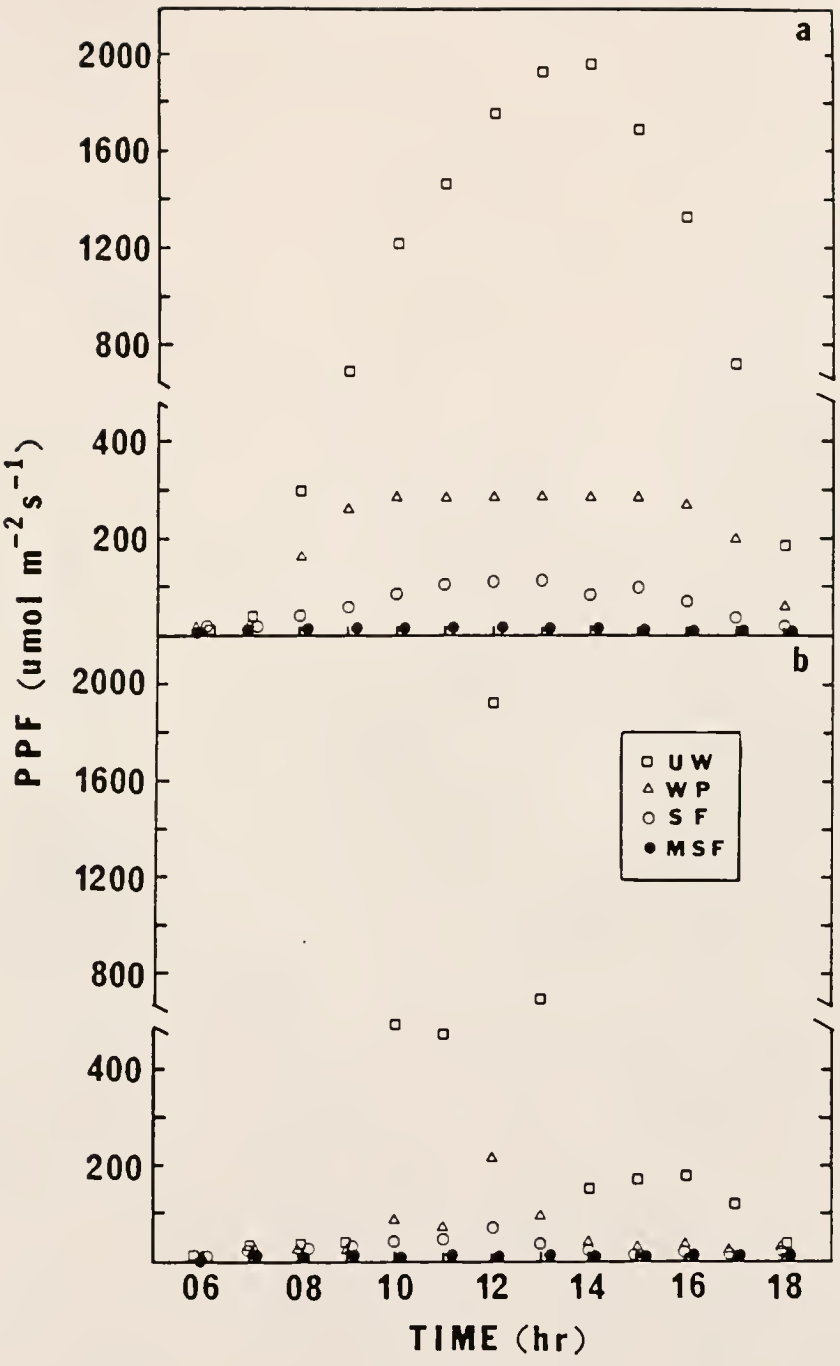


Fig. 5-2. Diurnal photosynthetic photon flux (PPF) underneath various trunk wraps on 2-year-old 'Hamlin' orange trees during a sunny day (a) and a cloudy day (b) in March, 1985. Each point represents a single measurement. No PPF was detected beneath CP and FG wraps. Abbreviations are as follows: unwrapped (UW), white polystyrene (WP), styrofoam (SF), and modified styrofoam (MSF).

Table 5-1. Numbers and dry weights of trunk sprouts on freeze damaged young 'Hamlin' orange trees on 13 May 1986 influenced by various trunk wraps.

Wrap type	Trunk sprouts (no.)	Dry wt (g)
Unwrapped	8.4a[z]	8.5a
White polystyrene	5.8a	3.1b
Modified styrofoam	1.5b	1.4b
Styrofoam	1.3b	2.5b
Fiberglass	0.0b	0.0b
Charcoal polystyrene	0.0b	0.0b

[z] Means followed by the same letter are not significantly different, Duncan's multiple range test, 5%. n=6.

statistically similar sprout number and dry weight, although no sprouts were found on any of the trunks in the FG and CP treatments. It is possible that sprouts had developed somewhat but abscised before 13 May in the FG and CP treatments due to the lack of PPF. Small etiolated sprouts have been observed under fiberglass wraps (Davies, unpublished). Jackson et al. (67) reported that sprouting occurred on 22% and 0% of freeze damaged trees with SF and FG wraps, respectively, which is qualitatively similar to the results in this study.

Some PPF (as low as 0.1% of ambient as in the MSF treatment) was necessary for development of trunk sprouts on freeze damaged trees. Furthermore, there was a direct correlation between PPF and sprout growth. This is supported by the fact that trunks receiving the highest PPF (UW and WP) had the highest number and dry weight of sprouts, trunks receiving no measurable PPF (FG and CP) had no sprouts, and treatments receiving intermediate intensities (SF and MSF) were intermediate in sprout number and dry weight.

It is possible that a PPF-temperature interaction occurred in this study, although unfortunately, the experiment was not designed for statistical analysis of interaction. However, some of the results may be explained better considering a PPF-temperature interaction. For example, the CP/WP treatment pair and the SF/MSF treatment pair were designed to create similar trunk thermal regimes but different PPF regimes. The WP and CP treatments both had relatively high mean temperatures and different PPF regimes, while the SF and MSF treatments both had relatively low mean temperatures and different PPF regimes. Large differences in sprouting occurred between the WP and CP treatments, suggesting that PPF influences sprout development given a

relatively high trunk thermal regime. On the other hand, no statistical differences in sprouting occurred between the SF an MSF treatments, suggesting that PPF does not control sprout development given a relatively low trunk thermal regime. Therefore, the effect of PPF on sprouting was either strong or nonexistent, depending on the trunk temperature regime.

Conclusions

In general, PPF was necessary for trunk sprouts to develop and persist under the various wraps, and both high PPF and high temperature favored the development of trunk sprouts. In relative terms, if the temperature was high but PPF low (as for CP), or temperature low and PPF high (as for SF), or both temperature and PPF were low (as MSF) then the number and dry weight of sprouts were reduced. Therefore, wraps that exclude light entirely are probably best for trunk sprout inhibition of moderately damaged young citrus trees where regrowth will occur on surviving canopy wood. If trees have been killed to the wrap, however, removal of the wrap at the earliest reasonable date would encourage development of trunk sprouts which will produce a new canopy.

CHAPTER VI
MODELING AND SIMULATION OF TREE WRAPS AND MICROSPRINKLER IRRIGATION FOR YOUNG CITRUS FREEZE PROTECTION

Introduction

Freeze protection using tree wraps and microsprinkler irrigation has been the subject of several field studies with young citrus trees (30, 32, 104, 107, 108). These studies mainly present data on trunk, leaf and air temperatures during freezes and resulting tree survival and regrowth. Although these studies demonstrate the effectiveness of tree wraps and microsprinkler irrigation for freeze protection under the conditions encountered, one can only speculate on the relative importance of humidity, air temperature, rate of air temperature decrease, windspeed, freeze duration, wrap type, water temperature, etc., on trunk temperature and subsequent tree survival. Freeze chambers cannot accurately simulate radiation, humidity, temperature and windspeed regimes observed in the field during freezes, hence laboratory studies would be neither practical nor useful in yielding accurate quantitative information. Alternatively, modeling and simulation of the wrap/microsprinkler system may provide detailed information that is currently lacking on system behavior, and can hasten the progress of research on freeze protection of young citrus trees by allowing investigators to study the problem year-round instead of only a few nights per year.

Models of overhead sprinkling for freeze protection have been used to predict irrigation requirements for successful freeze protection of

apple buds (109, 114) and mature citrus foliage (20, 46). Basically, these models calculate the rate of heat loss from a plant part under given freeze conditions, then use this to calculate the irrigation rate required to maintain the plant part above a predetermined critical temperature. Hence, output from sprinkler rate models consists of a single value, i.e., the irrigation requirement for freeze protection under a given set of environmental conditions (110). Practical applications of these models are limited because most irrigation systems are not designed to produce variable irrigation rates. However, concepts and information contained in sprinkler rate models were useful in developing a model of the tree wrap/microsprinkler irrigation system.

Rather than calculating static values of irrigation requirement, a more heuristic approach was taken to model the dynamic behavior of trunk temperature as influenced by the wrap/microsprinkler system given freeze conditions and other easily determined parameters. Using this approach, simulation experiments can be run and output, e.g., trunk temperature, evaluated at any time, under a variety of conditions. Furthermore, simulation can be used as a screen for hypotheses, reducing the amount of field experimentation necessary to achieve a particular goal. Ultimately, information can be derived that can be useful in redesigning and improving the system.

The primary objective of this research was to develop a process-based, dynamic heat transfer model of the wrap/microsprinkler system of young citrus freeze protection and use simulation to study system behavior. Simulations were run to assess the influence of parameters and environmental conditions on trunk temperature. Trunk

temperature predicted within one standard error of observed data during model validation were considered accurate.

Model Development

Description

The system under consideration consists of a young citrus tree trunk enveloped by an insulative tree wrap 8-14 cm in diameter and 30-40 cm in height (Fig. 6-1). Water is applied by a microsprinkler positioned 1 m from the tree, which consists of a plastic tube with an orifice and directional cap on the end that control the flow rate and spray pattern of the irrigation water. When the irrigation is on, the wrap surface is partially covered by a thin layer of water and an ice layer if conditions favor freezing. The wrap/ice mass intercepts a fraction of the irrigation water, and sensible or latent heat is transfered from the water to the wrap/ice surface. As ice accretes on the wrap surface, the fraction of water intercepted becomes greater as does the surface area over which water is distributed. In the field, some of the irrigation water often is intercepted by the canopy above the wrap, which in addition to protecting some of the canopy, can change the trunk temperature by flowing down the trunk inside the wrap.

Symbols used in model development, their definitions and units are listed in Table 6-1.

Heat Conduction within the Wrap and Trunk

The tree wrap system can be viewed as 2 main components: a cylinder of citrus wood (trunk) of variable radius, surrounded by an annulus of insulative material (wrap) of specified thickness and composition. Within the confines of the outer wrap surface, temperature varies spatially and temporally, hence the trunk/wrap composite cylinder is a

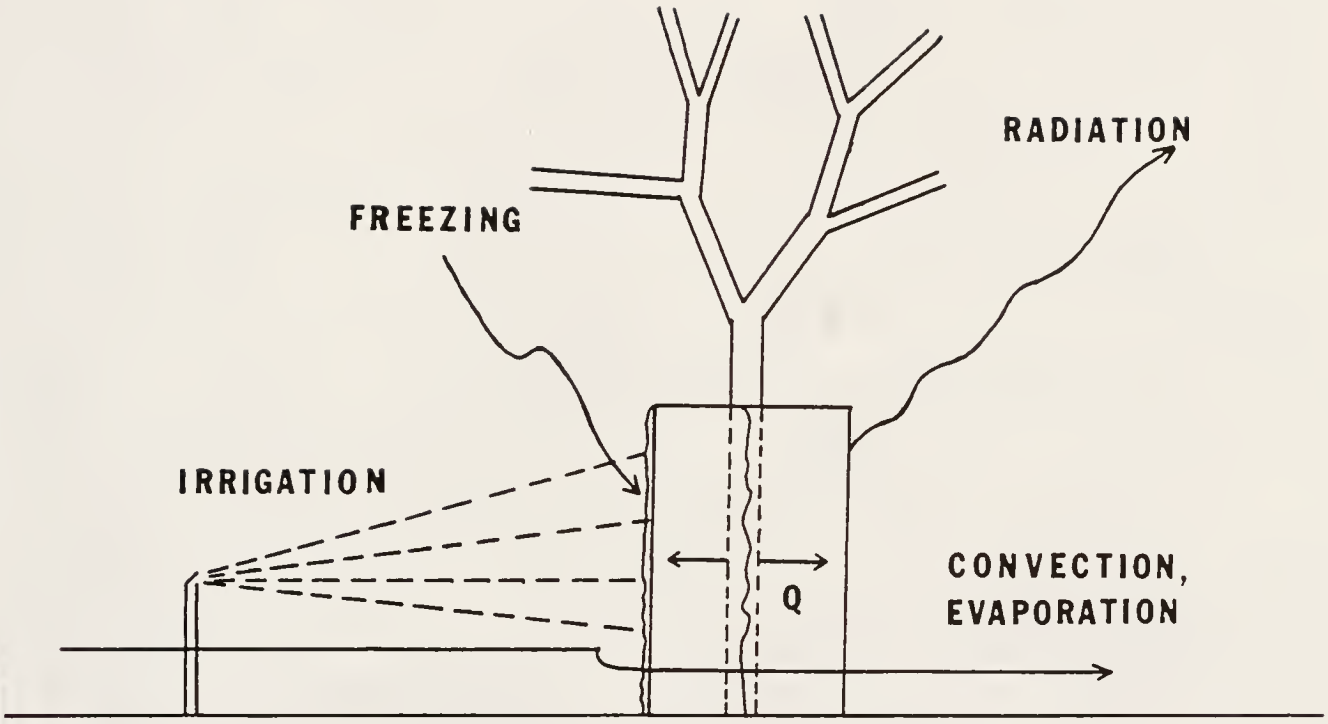


Fig. 6-1. Conceptual model of the tree wrap/microsprinkler irrigation system for young citrus freeze protection illustrating heat transfer processes; Q = heat conduction from within the trunk and wrap to the external boundary.

time-continuous, distributed thermal system. The mathematical model for the rate of change in temperature with time at any point within the trunk/wrap composite cylinder is developed for the case of one-dimensional (radial) heat flow in the following paragraphs.

The heat stored (h) per unit volume of a region within the trunk/wrap composite cylinder is defined as

$$h\ (\text{cal cm}^{-3}) = \rho\ c\ T \qquad [6\text{-}1a]$$

where c is the specific heat, ρ the density, and T the temperature of the region. In a time interval Δt, the change in heat content of a region of volume= $\Delta r\ r\Delta\theta\ \Delta z$ (Fig. 6-2) can be written as

$$\Delta r\ r\Delta\theta\ \Delta z \frac{\Delta h}{\Delta t} = \frac{\Delta T}{\Delta t} \rho\ c\ \Delta r\ r\Delta\theta\ \Delta z \qquad [6\text{-}1b]$$

where Δr, $r\Delta\theta$ and Δz are the infintesimal distance increments in the radial, angular, and vertical dimensions. The rate of change in heat content of the region must be equal in magnitude and opposite in sign to the change in flux (j) with distance (Δr), according to the principle of continuity (26)

$$\frac{\Delta(h\ \Delta r\ r\Delta\theta\ \Delta z)}{\Delta t} = -\ \frac{\Delta(j\ \Delta r\ r\Delta\theta\ \Delta z)}{\Delta r} \qquad [6\text{-}2a]$$

The terms Δr, $\Delta\theta$, and Δz are independent of time and radius, and r is independent of time, so [6-2a] can be rewritten as

$$\Delta r\ r\Delta\theta\ \Delta z \frac{\Delta h}{\Delta t} = -\ \frac{\Delta(rj)}{\Delta r} \Delta r\ \Delta\theta\ \Delta z \qquad [6\text{-}2b]$$

Cancelling like terms and taking the limit as Δt and Δr approach zero,

$$\frac{\partial h}{\partial t} = -\frac{1}{r}\frac{\partial (rj)}{\partial r} \qquad [6\text{-}3]$$

The flux in the radial direction j can be defined as

$$j = -K\frac{\partial T}{\partial r} \qquad [6\text{-}4]$$

where $\partial T/\partial r$ is the temperature gradient between the inner and outer surfaces of the region, and K is the thermal conductivity of the region. Substituting for j in [6-3] yields

$$\frac{\partial h}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r K \frac{\partial T}{\partial r}\right) \qquad [6\text{-}5]$$

Assuming K is constant with respect to r, and substituting [6-1a] for h

$$\frac{\partial T}{\partial t} = \alpha \frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\partial T}{\partial r}\right) \qquad [6\text{-}6]$$

where $\alpha = K/(\rho c)$, the thermal diffusivity of the region.

Similar derivations hold for the other 2 dimensions, resulting in the following form for 3-dimensional heat transfer in cylindrical coordinates (26)

$$\frac{\partial T}{\partial t} = \alpha \frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2} \qquad [6\text{-}7]$$

Thus, the rate of temperature change of any region between the trunk center and wrap surface is dependent on the thermal diffusivity and temperature gradients in the radial, circumferencial and vertical dimensions about the region.

Equation [6-7] was not solved analytically due to its complexity, and the fact that the parameters K, ρ, and c change discretely with r at the trunk/wrap interface. Instead, a finite difference version of [6-7] was employed to calculate rates of change in temperature, where second derivatives were approximated by second forward differences (26)

$$\frac{dT_{r,\theta,z}}{dt} = \alpha \left[\frac{(T_{r+1,\theta,z} - 2T_{r,\theta,z} + T_{r-1,\theta,z})}{\Delta r^2} + \frac{1}{r} \frac{(T_{r+1,\theta,z} - T_{r-1,\theta,z})}{2\Delta r} \right.$$

$$+ \frac{1}{r^2} \frac{(T_{r,\theta+1,z} - 2T_{r,\theta,z} + T_{r,\theta-1,z})}{\Delta\theta^2}$$

$$\left. + \frac{(T_{r,\theta,z+1} - 2T_{r,\theta,z} + T_{r,\theta,z-1})}{\Delta z^2} \right] \qquad [6\text{-}8]$$

Hence, if α and the temperatures of the 6 surrounding regions are known or set to assumed initial conditions, the rate of temperature change of any region within the trunk/wrap cylinder can be calculated.

In order to use [6-8], the distributed tree wrap system was divided into concentric layers in the radial direction, pie-shaped regions in the angular direction, and disc-shaped regions in the vertical direction yielding a discrete model system (Fig. 6-2). Therefore, the model system had a finite number of regions of heat storage each with a single temperature at any time t, whereas the real system contains an infinite number of different points and temperatures. Values of $\Delta\theta$ and Δz were set at 0.63 radians (36°) and 1.0 cm, respectively, and Δr was either 0.2 or 0.5 cm, which were the maximum achievable without affecting simulation output, allowing the programs to run in the least amount of time possible. Using these values there were 5200 (Δr=0.5) or 13000 (Δr=0.2) finite regions of heat storage for a typical trunk/wrap composite cylinder 13 cm in diameter and 40 cm in height.

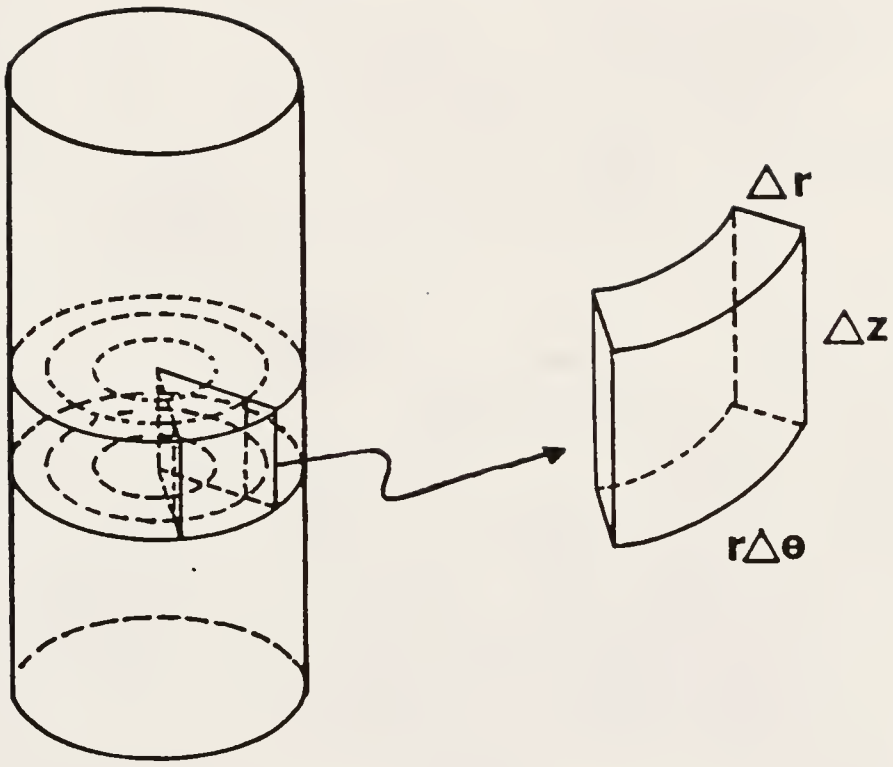


Fig. 6-2. Three-dimensional representation of the model system showing a representative finite region of heat storage. For a typical tree wrap 13 cm in diameter and 40 cm in height there were 5200 regions when $\Delta r=0.5$ cm, $\Delta\theta=0.63$ radians, and $\Delta z=1.0$ cm.

The temperatures of most interest are those corresponding to the cambial region of the trunk, because adventitious buds arise from this area to produce a new canopy. The cambium of a fully acclimated citrus tree is killed at temperatures of about -6.7° C (157), and it is important to know conditions under which the wrap/microsprinkler system allows the temperature of the cambium to reach critical values.

After rates of change were calculated, state variables were updated by Euler or rectangular numerical integration with respect to time

$$State_t = State_{t-dt} + dt(Rate_{t-dt}) \qquad [6\text{-}9]$$

where subscripts t and t-dt denote current and previous times. Temperature was the only state variable of interest in simulations except for ice layer thickness, which appeared in only those runs of the irrigation simulation which had rather severe simulated environmental conditions.

The Euler method assumes that the rate of change of a state variable is constant over the time period dt, hence dt must be small enough to justify this assumption. The maximum useful time step in heat transfer simulations is a function of thermal diffusivity and distance increment (dx), and generally is described as (26)

$$dt < \frac{(dx)^2}{2\,\alpha} \qquad [6\text{-}10]$$

where the calculation is for the component in the system with the highest α and lowest dx. Time steps of 0.3 or 0.8 seconds were used when simulating freeze protection with wraps and irrigation or wraps alone respectively, due to the different assumptions made in each case (see section on simulation). Greater time steps caused unstable oscillations of temperatures with time that were fatal to program execution, while lower time steps did not affect output.

Heat Exchange at the System Boundaries

Internal boundary

The internal boundary of the model system is the center of the trunk, and its rate of temperature change cannot be calculated using [6-8] because r=0 at the internal boundary, and [6-8] requires the temperature at r-1 for calculating radial heat transfer. Therefore, the temperature of the internal boundary was assummed to equal the average temperature of the adjacent regions, (i.e., where r=1). This assumption is often made with cylindrical thermal systems (26).

External boundary

Energy is exchanged between the system and the environment across the external system boundary, or outermost layer of the system, by the following processes: irrigation (IR), radiation (R), evaporation (E), and convection (CV) (Fig. 6-1). Conduction (Q) allows heat transfer to and from the external boundary, and therefore provides the linkage between heat transfer at the surface and that within the system. The external boundary differs in composition in both space and time, being either wrap material, water or ice, and it is necessary to determine its state before calculating the energy balance. However, a general form of the energy balance of the external boundary is

$$\Delta r(\rho\ c)_s \frac{dT_s}{dt} = (Q+IR-R-CV-E) \qquad [6\text{-}11]$$

where the subscript s denotes the external system boundary, and Δr its thickness. If the irrigation is on, the external boundary is a thin water layer where water is striking the wrap surface. Field observations indicated that the thickness of the water layer was about 0.1 cm, and this value was used in all simulations. If the irrigation

is off but an ice layer is present, then IR=0 and E represents sublimation instead of evaporation. Volume changes upon freezing of water are assumed negligible, and Δr remains equal to 0.1 cm when the system boundary is an ice layer. If the system boundary is wrap material (no irrigation or ice), then IR and E equal 0 and Δr becomes the thickness of the wrap surface layer, which was either 0.2 or 0.5 cm, similar to other wrap layers. Use of Δr in [6-11] implicitly assumes that temperature changes of the system boundary occur uniformly throughout its volume, which may only be true for small values of Δr.

Process descriptions

The heat transfer processes in the right hand side of [6-11] (Q, IR, E, CV, R) require specific mathematical descriptions, and all must be in the same units (cal cm^{-2} s^{-1}) to be summed as shown yielding the rate of temperature change of the external system boundary. The irrigation process is given by

$$IR = [RATE\ c_{H2O}\ (T_{H2O} - T_s)]/AREA \qquad [6\text{-}12]$$

where RATE is the amount of water intercepted by the wrap in liters per second, AREA is the surface area over which the water is uniformly distributed, T_{H2O} and c_{H2O} are temperature and specific heat of water respectively, and T_s is the temperature of the external boundary. In [6-12] it is evident that as T_{H2O} approaches T_s, IR approaches 0 regardless of RATE.

Conduction (Q) of heat to the external boundary from within is given by (128)

$$Q = K(T_{in} - T_s)/\ [r_s\ \ln(r_s/r_{in})] \qquad [6\text{-}13]$$

where T_{in} and r_{in} are the temperature and radius of a specified region internal to the external boundary. For example, if the outer system

boundary is wrap material, then T_{in} and r_{in} are the temperature and radius of the wrap layer beneath the wrap surface layer. Alternatively, if the external boundary is water, then T_{in} and r_{in} would correspond to the temperature and radius of the ice layer or the wrap surface layer, depending on presence or absence of ice.

Radiative heat transfer is given by

$$R= 4\sigma T_a^3 (T_s-T_a) \qquad [6\text{-}14]$$

where $4\sigma T_a^3$ is the radiative heat transfer coefficient (46, 111). The emmissivity of the surface is assumed to equal 1, and is therefore omitted in [6-14]. Some of the consequences of this assumption are discussed in chapter VII.

Evaporative heat flux is calculated by multiplying the mass flux of water vapor from the external boundary by the latent heat of vaporization (or sublimation)

$$E= L_v [D_{wv} Sh(W_s-W_a)] \qquad [6\text{-}15]$$

where D_{wv} is the water vapor diffusivity of air, L_v is the latent heat of vaporization (or sublimation), W_s and W_a are water vapor concentrations of the external boundary and air, respectively, and Sh is the Sherwood number which embodies windspeed and wrap dimensions (93). Water vapor concentration of the air (W_a) is calculated from air temperature and relative humidity using the psychrometric equation. The air adjacent to the external boundary is assumed to be saturated with water vapor at the surface temperature (W_s) if the external boundary is water or ice. Evaporative heat flux equals 0 if the external boundary is wrap material.

Convective heat transfer was calculated using Monteith's (93) equation for cylinders

$$Cv = (K_a Nu)/d \quad (T_s - T_a) \qquad [6\text{-}16]$$

where $(K_a Nu)/d$ is the convective heat transfer coefficient (93, 109), and Nu is the Nusselt number embodying windspeed, wrap dimensions, and kinematic viscosity of air.

Freezing of water on the external boundary invokes a boundary condition where the temperature at the ice-water interface is 0° C. The radius of the ice-water interface (r_{i-w}) is therefore important, and it is determined by calculating the rate of ice accretion, dr_{i-w}/dt. The rate of heat conduction away from an ice-water interface (Q_{i-w}) is (61)

$$Q_{i-w} = L_f \left(\rho_i \frac{dr_{i-w}}{dt}\right) \qquad [6\text{-}17]$$

where L_f is the latent heat of fusion, and ρ_i is the density of ice. Latent heat produced at the interface can move in 2 directions, either out (Q_{out}) into the water layer or in (Q_{in}) towards the wrap surface, hence

$$Q_{i-w} = \left| Q_{in} \right| + \left| Q_{out} \right| \qquad [6\text{-}18]$$

and,

$$Q_{in} = K_i \, (T_i - 273)/(r_{i-w} \ln(r_{i-w}/r_i)) \qquad [6\text{-}19]$$

$$Q_{out} = K_{H2O} \, (273 - T_{wl})/r_{wl} \ln(r_{wl}/r_{i-w}) \quad (r_{wl}/r_{i-w}) \qquad [6\text{-}20]$$

where T_i, r_i and T_{wl}, r_{wl} are the temperatures, radii of the ice layer and water layer adjacent to the interface, respectively. Substituting [6-19] and [6-20] into [6-17] and rearranging

$$\frac{dr_{i-w}}{dt} = (Q_{out} - Q_{in})/(L_f \rho_i) \qquad [6\text{-}21]$$

The radius of the ice-water interface is obtained by numerical integration of [6-21] yielding ice thickness, and adding to it the radius of the wrap.

Forcing Functions

The forcing functions or inputs required by the model are soil and air temperatures, windspeed, and relative humidity as functions of time. Forcing functions are independent variables that "force" the system to change state, and their magnitudes are not affected by the state of the system. With the exception of soil temperature, environmental variables are readily available in the form of weather forecasts or can be measured with hygrothermographs and anemometers. Soil temperatures must be measured with thermocouples or similar devices near the trunk and just below the soil surface. However, excluding the terms for vertical heat transfer in [6-8] allows for independence of the model from soil temperature data, which is desirable provided model behavior is not greatly altered.

Simulated air and soil temperatures decreased with time from initial values to desired minima by linear or negative exponential functions. Relative humidity was either held constant, or allowed to increase or decrease linearly with time as is often observed during a freeze. Wind velocity oscillated around a mean value as a sinusoidal function of time with a given amplitude and a period of about 30 min to approximate the stochastic nature of wind velocity observed on freeze nights.

Parameters

Most of the parameters used in the model were obtained from handbooks (128, 134), and parameters that could not be obtained from the

existing literature were estimated through laboratory or field experimentation. The latter included the thermal properties of tree wraps and some of the characteristics of the irrigation process. The determination of K, ρ, c and α of various tree wraps was rather involved, and is left for discussion in Chapter VII. Parameters used in the simulation programs are listed in appendices A and B.

Four characteristics of the irrigation process were required prior to simulation: water temperature, fraction intercepted by the wrap, amount of the wrap surface covered with water and distribution of the water on the wrap surface.

Temperature of the water striking the wrap surface was estimated with thermocouples on the surface of fiberglass wraps directly in the path of the water spray. Wraps were placed around trunks of 6, 2-year-old 'Hamlin' orange trees and temperatures were recorded hourly as trees were irrigated with 38 liter hr^{-1} emitters during 4 mild freeze nights in Jan.-Feb. 1987. Similar data were collected during Dec.-Jan. 1985-86 on wrapped 'Hamlin' orange trees irrigated with 38 and 57 liter hr^{-1} microsprinklers. Water temperature striking the surface ranged from 10° to 15° C and was relatively constant over time and freeze conditions.

To estimate the fraction of water intercepted, a fiberglass wrap placed around 2.5 cm polyvinyl chloride pipe was hung over a bucket, and irrigation water applied to the wrap for 20 to 30 min using 38, 57, and 87 liter hr^{-1} microsprinklers. Water that dripped from the wrap was collected and its volume measured in a graduated cylinder. The volume intercepted was divided by the total volume of water leaving the microsprinkler during the same time period to give the fraction

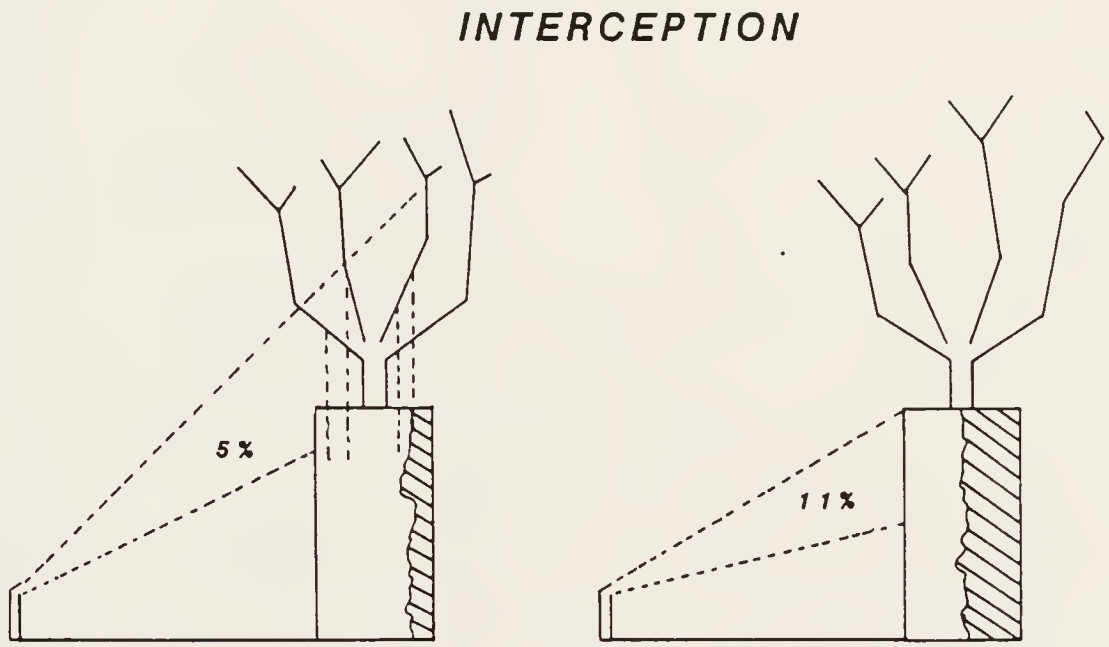


Fig. 6-3. Schematic diagram of interception of irrigation water by the tree wrap when microsprinklers were positioned so that water sprayed above the top of the wrap (left side), or only on the wrap surface (right side). Hatching indicates areas not covered by water.

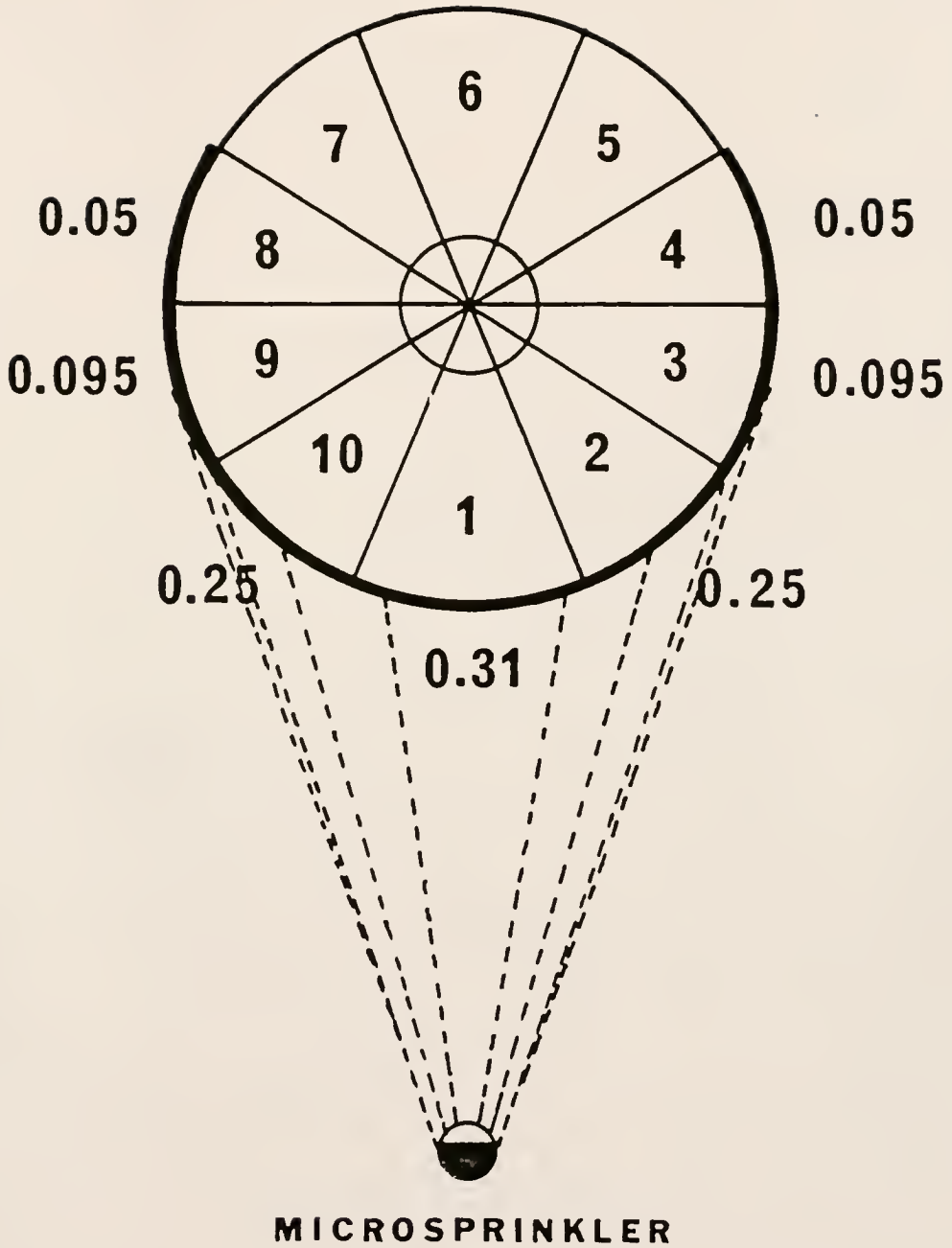


Fig. 6-4. Cross-section of the model system showing 70% coverage of the wrap surface with water (sections 1-4,8-10). The numbers associated with each section indicate the relative amount of intercepted water distributed uniformly over the surface area of the section.

intercepted. Values ranged from 0.05-0.11 depending on orientation of the microsprinkler, being lowest when some water sprayed above 40 cm (top of the wrap) and highest when water sprayed no higher than 40 cm (Fig. 6-3). Interception values were adjusted accordingly in simulations as ice accreted on the wrap and produced a larger surface for interception.

The percentage of wrap surface covered by water and/or ice and the distribution of water around the wrap surface are closely related. These parameters vary with freeze conditions and canopy morphology, and are difficult to measure in the field. The surface layer of the wrap was equally divided into 10 sections, and each section was treated separately in order to vary the coverage and distribution of water around the wrap surface (Fig. 6-4). On the surface towards the microsprinkler, all sections were assumed to be covered with water, with distribution was highest for the section 1, intermediate for sections 10 & 2, and lowest for peripheral sections 9 & 3. Values of distribution on the surface towards the microsprinkler are proportional to the area of a plane normal to the streamlines of the irrigation water in each section. Water can reach the surface opposite the microsprinkler (sections 4-8) after being deflected or dripped from the canopy, allowing some or all of these sections to be covered with water and/or ice. Field observations suggested that only sections 8 and 4 received any water except during severe freezes when all sections could be covered with ice and water. Therefore, the total amount of wrap surface covered by water/ice was estimated to be 70% for most simulations, but provisions were made in simulation programs for varying this value between 50-100% in increments of 10%. The volume of water distributed

on the wrap surface away from the microsprinkler was uncertain as well, but like percent coverage, it could be varied in simulation programs.

Water deflected or dripped from the canopy onto the wrap surface creates variability in characteristics of the irrigation water by increasing interception, changing distribution, and lowering water temperature due to contact with lower temperature objects and longer distances traveled. While this may not be a factor on the wrap surface towards the microsprinkler where direct interception prevails, it is an important consideration for the wrap surface opposite the microsprinkler because the only water reaching this area is that deflected or dripped from the canopy. Additionally, water striking the canopy has been observed to flow down the trunk underneath wraps in the field and reduce trunk temperature by as much as 6° C at the 20-cm height on mild freeze nights. The same process probably increases trunk temperatures on severe freeze nights when trunk temperature normally would drop below 0° C in the absence of liquid water inside the wrap. There is no provision in the model to account for water flowing down the trunk and changing its temperature. This factor, along with the degree of uncertainty with which the above characteristics of irrigation water are known, decreases the likelihood of accurate trunk temperature predictions in irrigation simulations.

Simulation

Simulation programs for the model system were written in FORTRAN and run on a Digital Vax-11 computer. Separate programs were developed for tree wraps alone and for irrigation and wraps together, because different simplifying assumptions were made in each case.

Simulation of Freeze Protection with Tree Wraps

Heat transfer in the angular direction was disregarded when simulating tree wraps alone, which assumes that temperature does not vary with position around the system at any given radius r and height z. This is a reasonable assumption because temperatures at various positions around the trunk and wrap surfaces at a given height are observed to be nearly equivalent in the field. Additionally, it was found that trunk surface temperatures predicted when considering only radial heat transfer were within $\pm$ 0.3° C of those predicted for the 20-cm height when considering both radial and vertical heat transfer (See Fig. 7-3). Trunk temperatures at the 20-cm height were roughly averages of those for the 1 and 40-cm heights, and disregarding vertical heat transfer resulted in prediction of a single average trunk temperature. Disregarding the vertical dimension allowed independence from soil temperature data if trunk temperatures corresponding to the 20-cm height only were desired, and the simplified program for 1-dimensional (radial) heat transfer ran in 95% less computer time than the 2-dimensional (radial and vertical) program.

In both the 1- and 2-dimensional simulations, the rate of temperature change at the wrap surface was calculated using equation [6-11] (disregarding terms for irrigation and evaporation) after obtaining values of Q, CV, and R. The terms for angular heat transfer (and vertical heat transfer for 1-dimensional simulation) were deleted from [6-8] to calculate rates of temperature change throughout the wrap and trunk. Distance increments in the radial (Δr) and vertical (Δz) directions were set as high as possible without sacrificing accuracy,

which after many simulation trials, were determined to be 0.2 cm and 1.0 cm, respectively.

Simulation of Freeze Protection with Microsprinkler Irrigation and Tree Wraps

Heat transfer in the vertical direction was disregarded when simulating wraps and irrigation together, which assumes that vertical heat transfer has no effect on temperature in the model system. This is a reasonable assumption because omitting vertical heat transfer in the wrap simulation resulted in prediction of an average trunk temperature, or that for the 20-cm height (see Chapter VII). Furthermore, the 3-dimensional heat transfer simulation used 8 hr of computer time for each hr of time simulated, hence heat transfer in one dimension had to be disregarded to allow the simulation to run in a managable time period. The vertical dimension was the obvious choice for omission because temperature gradients were lower and distances greater than the other dimensions, and simulations ran about 50 times as fast without vertical heat transfer calculations.

The outer system boundary was either water, ice or wrap material, depending on water distribution and the point on the wrap surface being considered. The rate of temperature change of the system boundary was calculated using [6-11], omitting terms E and IR for areas of the wrap surface not covered by water. Heat transfer in the ice and water layers was assumed to occur in only the radial direction which simplified calculations of energy transfer for the outer system boundary. A subroutine for ice accretion using equations [6-17]-[6-21] was accessed if the temperature of the water layer was $< 0°$ C or if an ice layer was already present.

Equation [6-8] without terms for vertical heat transfer was used to calculate rates of temperature change throughout the wrap and trunk. The radial (Δr) and angular ($\Delta\theta$) distance increments were set at 0.5 cm and 0.63 radians (36°) respectively, which were the maximum achievable without affecting model output. As for the tree wrap simulations, Δr and $\Delta\theta$ were determined after many simulation trials to increase speed of program execution.

Table 6-1. Definition of symbols used in model development.

Symbol	Definition
AREA	surface area of wrap (cm^2)
c	specific heat (cal g^{-1} $°K^{-1}$)
Cv	convective heat flux (cal cm^{-2} s^{-1})
d	characteristic dimension (cm)
D	diffusion coefficient (cm^2 s^{-1})
E	evaporative heat flux (cal cm^{-2} s^{-1})
h	heat content (cal cm^{-3})
IR	sensible heat flux from irrigation water (cal cm^{-2} s^{-1})
j	heat flux (cal cm^{-2} s^{-1})
K	thermal conductivity (cal cm^{-1} s^{-1} $°K^{-1}$)
L	latent heat (cal g^{-1})
Nu	Nusselt number (dimensionless)
Q	heat conduction (cal cm^{-2} s^{-1})
R	radiative heat flux (cal cm^{-2} s^{-1})
RATE	irrigation rate (liter s^{-1})
r	radius (cm)
Sh	Sherwood number (dimensionless)
T	temperature (°K or °C)
t	time (s)
W	water vapor concentration (g cm^{-3})
z	vertical distance (cm)
α	thermal diffusivity (cm^2 s^{-1})
ρ	density (g cm^{-3})
σ	Stephan-Boltzmann constant (cal cm^{-2} s^{-1} K^{-4})
θ	angular distance (radians)
Δ	"change in"

Subscripts

a	air
f	fusion
H_2O	water
i	ice
in	interior region
i-w	ice-water interface
out	outer or exterior region
r	radial coordinate
s	system boundary
t	time
v	vaporization
wl	water layer
wv	water vapor
z	vertical coordinate
θ	angular coordinate

CHAPTER VII
THERMAL PROPERTIES AND SIMULATION OF FREEZE PROTECTION PERFORMANCE OF TREE WRAPS FOR YOUNG CITRUS TREES

Introduction

Traditionally, young citrus trees have been protected from freezing injury by banking soil around trunks during periods of cold weather (59). Following severe freezes, the tree canopy above the soil bank is killed, but after removal of the bank trees sprout from the surviving wood and produce new canopies. Although an effective means of freeze protection, construction and maintenance of soil banks often causes mechanical or disease damage to trunks, and are labor intensive. For these reasons, tree wraps made of inert insulating materials were introduced in Texas in the mid-1950's (80) and are now used in other citrus growing areas. It was thought that wraps could provide freeze protection similar to soil banks, but unlike soil banks could be left in place for 3-4 years, until the tree was better able to survive freezes by itself. However, trunk temperatures under soil banks typically typically 8° C higher than air temperature, but only 0° to 4° C higher than air temperature under tree wraps (67, 68, 121, 170).

Despite lower potential for freeze protection, wraps are widely used because they provide sprout inhibition and protection from herbicide, fertilizer and mechanical injury. Wraps composed of dried plant materials have been used in California to protect trunks from wind, rodent and radiation damage (129). Furthermore, wraps augment the

effect of microsprinkler irrigation during freezes, providing greater freeze protection than microsprinkler irrigation or wraps alone (30).

Reasons for unpredictable levels of freeze protection provided by wraps are unclear, although trunk and wrap diameter (170), rate of air temperature decrease (121), and freeze duration probably are important factors. Fucik and Hensz (39) tested various wraps in a freeze chamber and suggested that wraps which caused the bark temperature to decrease at about 50% (or less) of the rate of air temperature decrease would provide trunk protection during most freeze conditions. However, Davies et al. (31) observed similar rates of trunk and air temperature decrease with soil banks; thus a nearly constant difference between trunk and air temperature was maintained during freeze events due to initially higher trunk temperatures and/or a delay in the commencement of trunk temperature decrease. Because soil banks provide greater protection than wraps, the suggestion of Fucik and Hensz that relative rates of bark and air temperature decrease are indicative of freeze protection capability is true only under certain circumstances.

Turrell (129) compiled a list of thermal properties of some materials used in wraps and suggested that thermal diffusivity is the single most important factor determining the freeze protection potential of a wrap. While this may be true, it provides only a qualitative understanding of wrap performance, and quantitative estimates of margins of protection among materials differing in thermal diffusivity remain unclear. It is difficult to assess in field studies the relative importance of thermal diffusivity and other factors on wrap performance, and radiation and windspeed regimes cannot be simulated accurately in a freeze chamber.

Modeling and simulation provide a means by which tree wraps can be studied quantitatively. The objectives of this research were to measure the thermal properties of tree wraps in-situ and use the simulation model of the tree wrap system in Chapter VI to analyze wrap performance under various conditions.

Materials and Methods

Thermal Properties of Tree Wraps

Laboratory studies

Several tree wraps were chosen for analysis of thermal properties. Five replicates of each type were tested to obtain mean values of thermal conductivity (K), density (ρ), specific heat (c), and thermal diffusivity (α). Wraps ranged from 34-40 cm in height and 8-13 cm in diameter when properly installed. A thick-walled (2.5 cm) styrofoam wrap was analyzed with and without its 2 plastic containers of water inside (ca. 420 ml water). Yelenosky (156) provides a more detailed description of this wrap. Thin-walled (0.2 cm) polystyrene and thick-walled (1.8 cm) polyethylene foam wraps had the smallest diameters (ca. 8 cm) and like the styrofoam wrap, contained free airspaces between the inner wrap and trunk surfaces. Because the size of the airspace varies with trunk diameter, 2.4 cm was used for trunk diameter in volume-weighted calculations of ρ and c and in wrap simulations, unless otherwise indicated. The fiberglass wrap consisted of R-11 (9-cm thick) aluminum foil-faced fiberglass building insulation held in place around the trunk with wire mesh, and when newly installed there was no airspace between the trunk and inner wrap surface. Old fiberglass wraps which had been used for one season in the field and were somewhat weathered, and new fiberglass wraps wetted to a volumetric water content of about

0.125, were also studied. Except fiberglass, other wrap materials did not absorb water when submerged, nor did they become significantly weathered after one season's use.

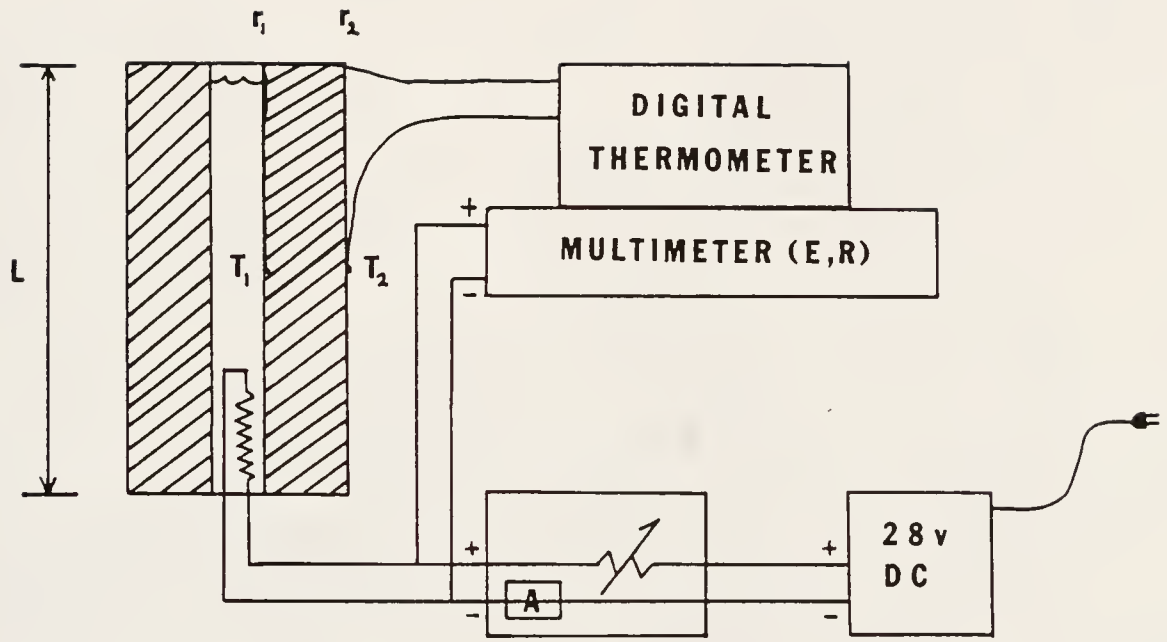
The thermal conductivity of various wraps was measured using an apparatus which consisted of a heating element inside a 4-cm diameter tube filled with water (Fig. 7-1). The heating element drew power from a 28 volt DC power source. Voltage (E) and resistance (R) across the heating element were measured with a Keithley multimeter, and energy flow (watts) into the heating element (Q) was calculated as E^2/R. Temperatures of the tube (T_1) and wrap surface (T_2) were allowed to reach a steady-state after placing the wrap around the tube (about 24 hr) at which time the electrical energy flow into the heating element equaled the heat flow radially outward through the wrap. The top and bottom of the wrap were insulated with 15-20 cm fiberglass to minimize vertical heat loss, which would have caused K to be overestimated. The steady-state equation for heat flow in cylindrical coordinates was solved for K (128)

$$K = \frac{Q \ \ln(r_2/r_1)}{(T_1-T_2) \ 2 \ \Pi \ L} \qquad [7\text{-}1]$$

where r_2 and r_1 are the radii (cm) of the outer wrap surface and water tube, respectively, and L is the wrap length (cm). Density was measured directly on pieces of wrap material, and c values were obtained from tables of thermal properties of insulation (128). Thermal diffusivity, α, was calculated as

$$\alpha = \frac{K}{\rho \ c} \qquad [7\text{-}2]$$

where ρ and c are volume-weighted averages of the wrap components.



$$Q\,(\text{watts}) = \frac{E^2}{R}$$

$$K = \frac{Q \cdot \ln(r_2/r_1)}{(T_1 - T_2) \cdot 2 \cdot \pi \cdot L}$$

Fig. 7-1. Schematic representation of the device used to measure the thermal conductivity (K) of tree wraps in-situ. See text for descriptions of components.

The relative freezing behavior of wet and dry fiberglass wraps was observed in freeze chambers to verify values of thermal properties obtained for these wraps. Two young citrus trunks ca. 2.4 cm in diameter were cut into 40-cm segments and each placed inside a dry and a wet fiberglass wrap. Thermocouples were attached at the 20-cm height on each trunk and on the surface of each wrap. Air temperature was decreased asymptotically to minima of -6° and -15° C over periods of 8 hr during 2 separate freezing cycles.

Field studies

The effects of water and ventilation in wraps were studied in the field. Fiberglass wraps with the water containers from styrofoam wraps inside were compared with normal fiberglass and styrofoam wraps on 4 mild freeze nights in 1987 for freeze protection capability. Three wraps of each type were placed around trunks of 2-year-old 'Hamlin' orange (Citrus sinensis (L.) Osb.) trees having similar diameters, and thermocouples were attached to each trunk at the 20-cm height in Dec. 1986. Minimum trunk and air temperatures were measured at sunrise on 12, 24, 28 Jan. and 10 Feb. 1987, and analyzed for significant differences using analysis of variance and Duncan's multiple range test.

Simulation of Freeze Protection Performance of Tree Wraps

A deterministic heat transfer simulation of the tree wrap system was developed using the discrete model system described in Chapter VI. Trunk temperature predicted by the model and measured in the field corresponded to the 20-cm height unless otherwise indicated. Details of field experiments used for validation with young 'Hamlin' orange trees have been described in Chapter III. Predicted trunk temperatures within one standard error of the mean observed value were considered accurate or valid.

One-dimensional (1-D) and 2-dimensional (2-D) models were used to simulate 5 freezes in 1985-86 for model validation because trunk temperature data were available and meterological conditions were highly variable among these dates. The 1-D model was used for all other simulations because it predicted trunk temperatures at the 20-cm height within $\pm$ 0.3° C of those predicted by the 2-D model, and used 95% less computer time. Environmental inputs were air temperature and windspeed, which were approximated as functions of time or held constant. The thermal properties of fiberglass wraps in Table 7-1 and α for citrus wood (131) were used in all simulations. Vertical temperature gradients in the 2-D model were initialized by assuming the trunk temperature 1 cm above the soil surface was equal to the soil temperature, and the trunk temperature at 40 cm was equal to the air temperature throughout the simulation. For validation, radial temperature gradients in both 1-D and 2-D models were initialized by setting trunk surface temperatures equal to observed initial values, and wrap surface temperatures equal to the initial air temperature. In other simulations, radial temperature gradients were assumed to be 2° C between the trunk to the wrap surfaces, as often observed in the field. Parameters used in simulations are given in appendix A.

Several simulation experiments were performed to address various aspects of interest, which involved little more than changing initial conditions, parameters, or forcing functions of the simulation prior to each run of the program. First, predicted trunk temperatures from simulation of past freezes were compared against observed trunk temperatures on those dates for model validation. Second, performance of 4 commercially available wraps was compared under typical freeze

conditions, along with a hypothetical wrap with the thermal properties of soil. Third, possible reasons for variation in the amount of freeze protection afforded by fiberglass tree wraps under different freeze conditions were investigated by varying the rate and pattern of air temperature decrease, and trunk and wrap diameter. Finally, the effects of windspeed and soil temperature on minimum trunk temperature of wrapped trees were investigated. A short explanation of each simulation experiment precedes a discussion of the results.

Results and Discussion

Thermal Properties of Tree Wraps

Laboratory studies

Measured K values for new fiberglass wraps were about 8% higher than the manufacturer's value of 1.07×10^{-4} cal cm^{-1} s^{-1} $°C^{-1}$ (personal communication, Certainteed Corp.), indicating that the device diagrammed in Fig. 7-1 measured K values with reasonable accuracy. Compression of the fiberglass around the water tube or vertical heat loss may have accounted for slightly higher measured values.

The styrofoam wrap had the lowest α (best insulator) followed by fiberglass, polyethylene and polystyrene (Table 7-1). This ranking generally agrees with the level of freeze protection observed in the field with these wraps. Davies et al. (30) found that polystyrene wraps caused higher daytime and lower nighttime trunk temperatures than fiberglass wraps, and in turn, styrofoam wraps dampened diurnal variation in trunk temperatures better than fiberglass. Jackson et al. (67) found styrofoam was the best insulator in their tests, followed by fiberglass and then styrofoam without its water containers, which also agrees with these data (Table 7-1). Data from Chapter V (see Fig. 5-1)

Table 7-1. Thermal conductivity (K), density (ρ), specific heat (c) and thermal diffusivity (α) of tree wraps used for young citrus freeze protection.

Wrap	Thermal property[z] K ($cal\ cm^{-1}\ s^{-1}\ k^{-1}$) ($x10^{-4}$)	ρ ($g\ cm^{-3}$) ($x10^{-2}$)	c ($cal\ g^{-1}\ k^{-1}$) ($x10^{-1}$)	α ($cm^2\ s^{-1}$) ($x10^{-2}$)
Styrofoam	2.56	13.3	3.5	0.55
Fiberglass (wet)	3.56	14.4	3.4	0.73
Fiberglass (new)	1.15	2.22	2.4	2.16
Fiberglass (old)	1.20	2.22	2.4	2.25
Styrofoam (no water)	2.49	1.88	2.6	5.09
Polyethylene	1.31	0.27	3.6	13.3
Polystyrene	2.27	0.62	2.4	15.3

[z] For K values n=5, for p values n=10, c values are single calculations and $\alpha = K/(\rho\ c)$.

further reflects the positive correlation between diurnal fluctuation of trunk temperature and wrap thermal diffusivity for styrofoam, fiberglass, and polystyrene wraps.

Wetting the fiberglass wrap caused a 3-fold increase in K, but increased ρ and c such that α was lower for wet than dry fiberglass (Table 7-1). Trunk temperature under a wet fiberglass wrap generally was 1° to 3° C higher than that of a dry wrap during a controlled freeze at -15° C, although both trunks eventually reached the same minimum temperature. However, when frozen at -6° C, trunk temperature under the wet wrap never went below 0° C, while that under the dry wrap was nearly -6° C, suggesting that latent heat produced by freezing of water within the wet wrap was sufficient to prevent trunk temperature from dropping below 0° C. Rose and Yelenosky (121) found trunk temperatures under wet fiberglass wraps to be 0.5° to 2° C higher than those for dry fiberglass during a controlled freeze at -8° C. They also found that temperatures under wet wraps decreased to 0° C and remained at this temperature for 4 hr, while temperatures under the dry wraps decreased steadily, consistent with the results obtained in the present study at -6° C.

Field observations indicated that new fiberglass wraps rarely retain water even after heavy rainfall or long periods of irrigation. Other investigators have reported that fiberglass wraps retain less than 10% of the initial volume of water 24 hr after saturation with 1.8 liters of water (121). In this research, it was difficult to wet fiberglass wraps to a volumetric water content of 0.125 by submergence due to their extreme hydrophobicity. Moreover, fiberglass insulation collapsed when thoroughly wetted, reducing wrap diameter and creating gaps and free airspaces. It is unlikely that wet fiberglass wraps would

provide greater freeze protection than dry fiberglass wraps under field conditions although data suggest otherwise (Table 7-1), because quantities of water retained are small (30 to 60 ml) (121) and gaps created upon collapse may allow heat to escape from the wrap.

The α of old fiberglass wraps was only 4% higher than that of the new fiberglass, indicating that after one season's use, fiberglass wraps retain most of their insulative capacity.

The styrofoam wraps with the water containers removed had a α nearly an order of magnitude higher than normal styrofoam wraps (Table 7-1). Thus, a relatively small volume of water within the styrofoam wrap greatly increases its insulative capacity. Furthermore, when water in the wrap freezes, latent heat production can maintain trunk temperatures at about 0° C for long periods of time under controlled freeze conditions (156). Field observations consistently show that styrofoam wraps provide more freeze protection than other types, but unlike performance in freeze chambers, they frequently allow trunk temperatures to drop below 0° C.

The thermal conductivity of the free airspace inside polystyrene and styrofoam wraps without water containers was calculated by measuring the temperature and radius of the inner wrap surface and substituting these values for T_2 and r_2 in equation [7-1]. Measured thermal conductivity values averaged 6.3 times higher than the standard conductivity of still air (5.78×10^{-5} cal cm^{-1} s^{-1} K^{-1}). Convection currents due to temperature gradients across the airspace probably were responsible for increased K. It follows that wraps which have free airspaces are potentially poorer insulators because convection currents can transfer heat rapidly from the trunk to the inner wrap surface and

subsequently out through the wrap. Although the styrofoam wrap has a free airspace, the water containers inside provide enough heat to offset the negative effect of the free airspace on wrap performance. Materials such as fiberglass are desirable in this respect because they normally lack free airspaces but allow for gas exchange and trunk expansion as the tree grows.

Field studies

Trunk temperatures under styrofoam wraps were significantly lower than those under fiberglass wraps with water containers inside on 3 out of 4 mild freeze nights in 1987 (Table 7-2). This occurred despite the fact that the α of styrofoam is 19% lower than that of fiberglass (data not shown), and the insulation thickness was similar for each wrap. However, styrofoam wraps differed from fiberglass wraps with water containers inside because the former had ventilation holes in the sides and top, whereas the latter did not. Ventilation holes in styrofoam wraps may have allowed air heated by sensible and latent heat from the water to escape, particularly under windy conditions, thereby reducing trunk temperatures. Styrofoam and fiberglass wraps with water containers inside had similar trunk temperatures on 24 Jan. possibly because convective heat loss from the styrofoam wrap airspace was minimized under the calm conditions which prevailed on this particular night. Styrofoam wraps with Blocked ventilation holes had higher nighttime and lower daytime trunk temperatures than those of ventilated styrofoam wraps (see Fig. 5-1), providing further support that ventilation increases heat exchange in styrofoam wraps. Fucik and Hensz (39) found that clamping the top of a corrugated cardboard wrap around a tree trunk increased its insulative capacity.

Table 7-2. Minimum trunk and air temperatures of young 'Hamlin' orange trees wrapped with fiberglass (FG), fiberglass with water containers (FGW), or styrofoam (SF) wraps on 4 mild freeze nights in 1987.

Tree wrap	Date			
	12 Jan.	24 Jan.	28 Jan.	10 Feb.
	Temperature (°C)			
FGW	2.2a[z]	-0.8a	1.5a	1.5a
SF	0.0b	-0.7a	-0.1b	-0.5b
FG	-0.4b	-2.0b	-0.5b	-1.2bc
AIR	-1.5c	-3.0c	-1.4c	-1.8c

[z] Means followed by the same letter within columns are not significantly different, Duncan's multiple range test, 5% level. For all temperatures, n=3. Trunk temperatures were measured at the 20-cm height underneath tree wraps.

Data for fiberglass wraps with water containers inside demonstrates the potential for improved freeze protection by a wrap which has desirable characteristics such as sprout inhibition (Chapter V) and durability, and is inexpensive and easy to install. Furthermore, commercially available wraps which use water containers (styrofoam) are more expensive and allow more trunk sprouting than fiberglass wraps (67, Chapter V). However, fiberglass wraps with water containers inside require field testing under more severe freeze conditions before they can be recommended for use on young citrus trees.

Simulation of Freeze Protection Performance of Tree Wraps

Validation

Trunk temperatures predicted by the model were generally 1 to 2° C higher early in the time interval of the freeze event, but within one standard error of observed mean values later (Fig. 7-2). Predicted minimum trunk temperature for the 20-cm height were regressed on observed trunk temperature using the 1-D model on the 5 nights shown in Fig. 7-2 a-e (square symbols in Fig. 7-3). Also, the minimum trunk temperature predicted for 3 different heights by the 2-D model were regressed against corresponding observed minima on the 3 nights in Fig. 7-2 c-e (circular symbols in Fig. 7-3). Data points in Fig. 7-3 lie reasonably close to the 1:1 correlation line and regression lines have slopes of 0.8 and 1.1 for 1-D and 2-D programs, respectively. The slope of the regression line for minimum temperatures on the 5 nights in Fig. 7-2 was < 1.0 because trunk temperature on the coldest night was overpredicted and trunk temperature on one of the warmest nights was underpredicted. The 2-D simulation tended to slightly over-predict trunk temperature 3 cm from the top and under-predict temperature 3 cm

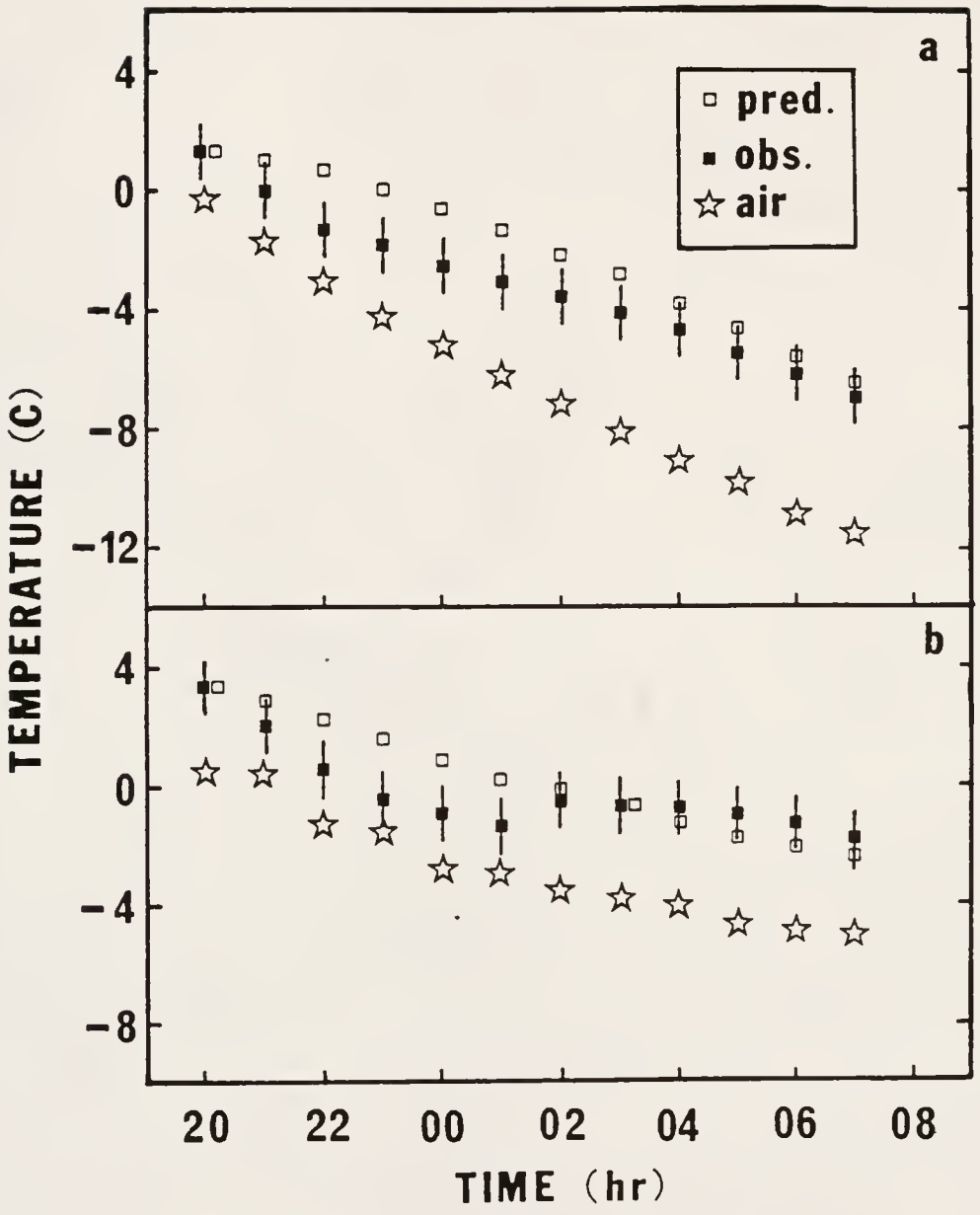


Fig. 7-2. Observed trunk (obs.) and air temperatures on 20-21 Jan. 1985 (a), 26-27 Jan. 1985 (b), 25-26 Dec. 1985 (c), 26-27 Dec. 1985 (d), and 27-28 Jan. 1986 (e), and predicted trunk temperatures (pred.) from simulation of the freezes. Observed trunk and air temperatures are means of 6 observations, while predicted trunk temperatures are single determinations. Bars attached to observed trunk temperature symbols are $\pm$ SE of the mean obtained from regression of observed trunk temperatures vs. time.

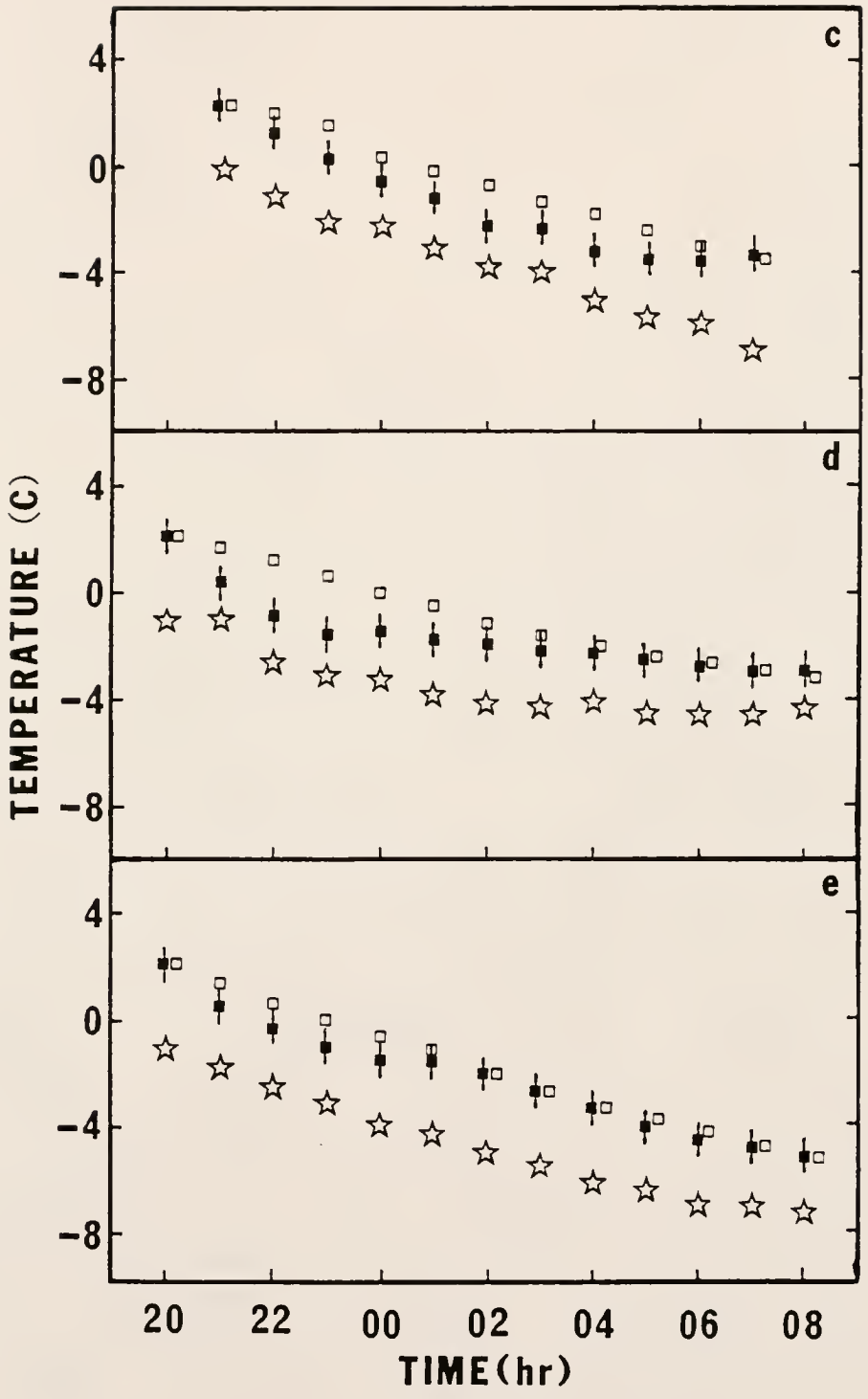


Fig. 7-2. -continued.

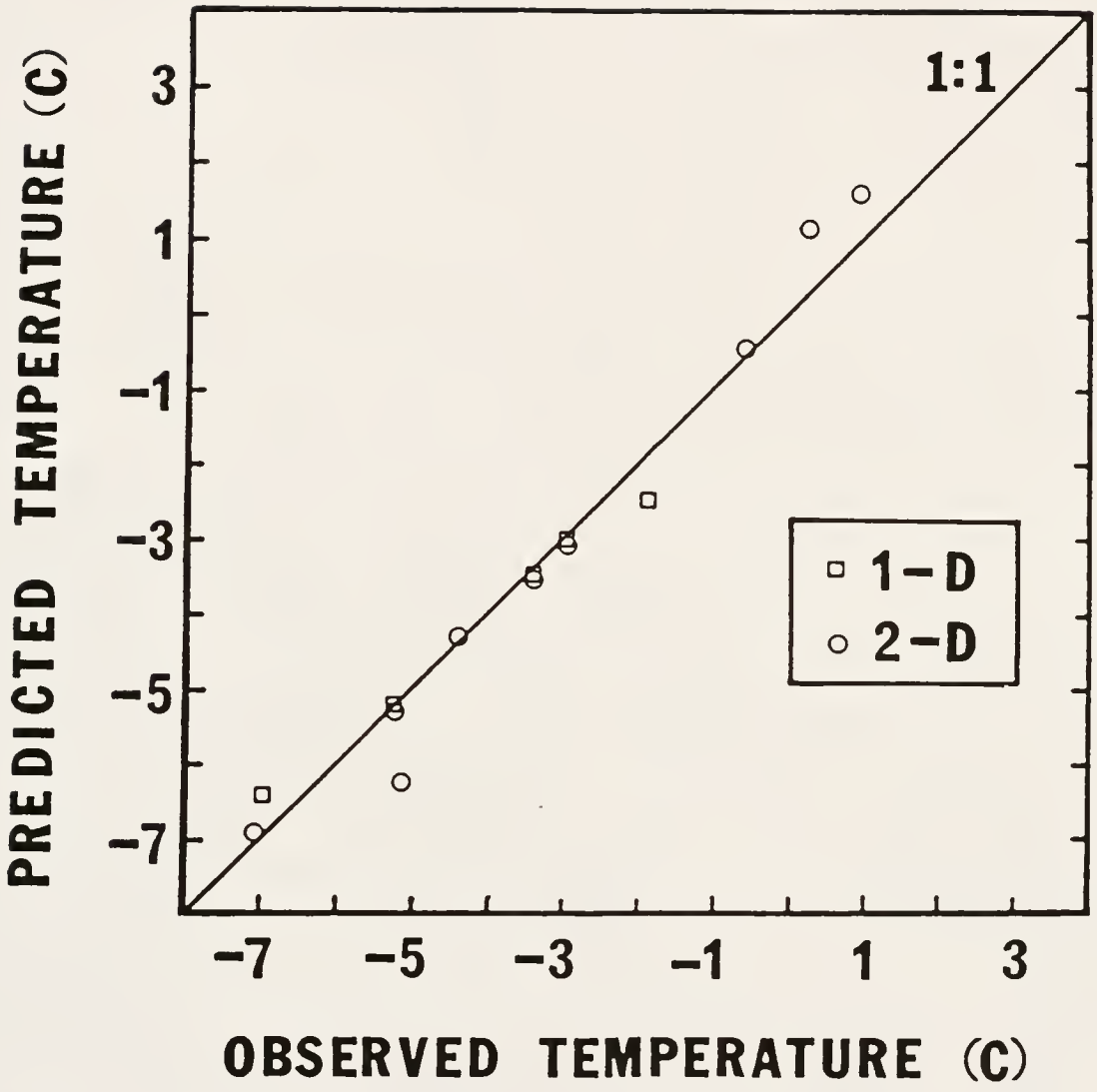


Fig. 7-3. Regression of predicted vs. observed minimum trunk temperature using 1-dimensional (1-D) and 2-dimensional (2-D) models. The square symbols are minimum trunk temperatures at 20-cm height for the 5 freezes in Fig. 7-2 a-e using the 1-D model, the circular symbols are for minimum trunk temperatures at the 3-, 20-, and 37-cm heights for 3 freezes in Fig. 7-2 c-e using the 2-D model. For the 1-D model, $n=5$, $y=0.8x - 0.8$, $r^2=0.98$; for the 2-D model, $n=9$, $y=1.1x + 0.5$, $r^2=0.98$. The solid line is a 1:1 correlation line.

from the base of the wrap (circles in upper right and lower left hand corner of Fig. 7-3, respectively), which caused the slope of the 2-D regression line to be slightly greater than one. Lower top and higher base temperatures on wrapped trunks have been observed in field studies with soil banks and fiberglass wraps (31, 80, 121), and lower temperatures at the top of the trunk may account for dieback into wraps as observed after severe freezes.

Two explanations can be made for over-prediction of trunk temperatures early in simulations. First, slight overestimation of trunk diameter and temperature gradients through the wrap and trunk caused temperatures to be a few tenths of a degree C higher overall, as verified by repeating the simulations with lower values of these parameters. Second, and most important, differences in heat transfer properties of the real and model systems, particularly within the wrap and trunk, may be responsible for inaccuracies in model behavior. Initially, temperature in the model system changes slowly in response to forcing functions. Later in the simulation, slightly faster rates of temperature decrease occur in the model than those in the real system. Further analysis showed that the aberrant model behavior could not be attributed to inaccuracies in thermal properties of tree wraps, time step, or distance increment. However, the data show that the model is able to simulate system behavior and can predict trunk temperature reasonably well, particularly at the 20-cm height and later in the simulation when critical temperatures are reached.

Simulation of tree wrap performance

Freeze protection provided by 4 commercial wraps was assessed using thermal properties in Table 7-1 during a simulated freeze where air

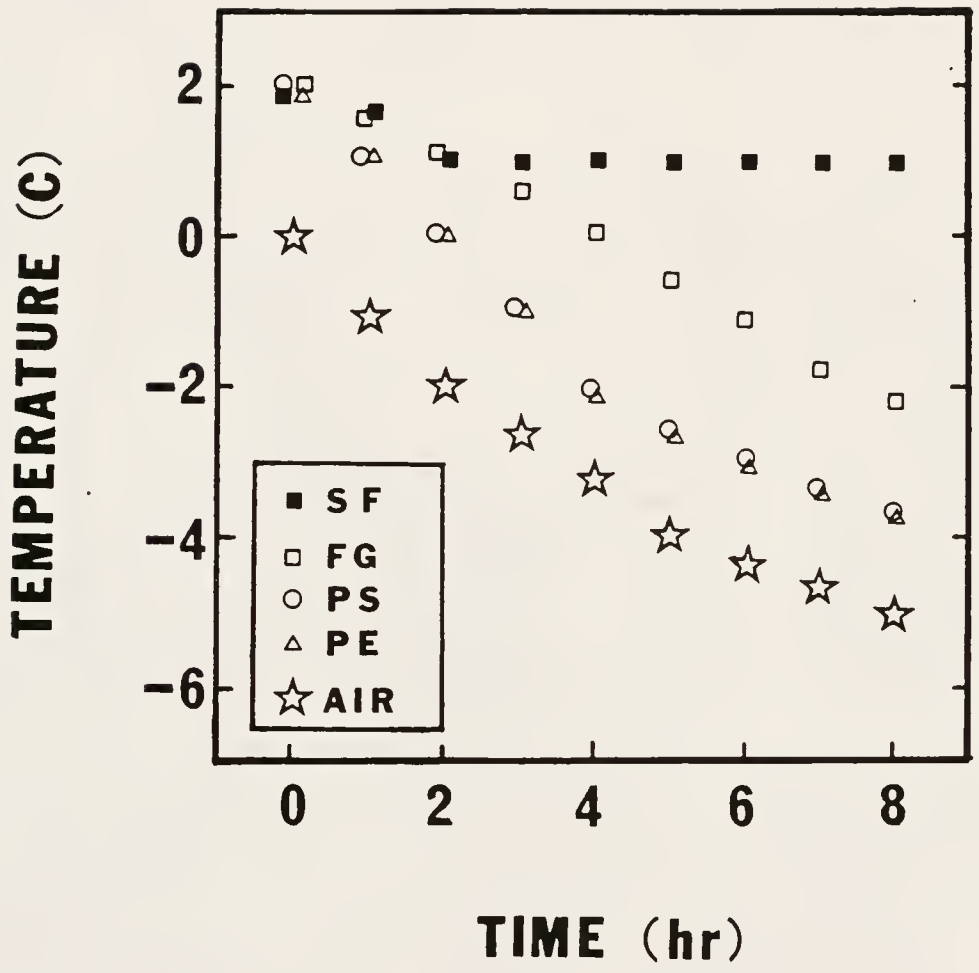


Fig. 7-4. Predicted trunk temperatures for 4 commercially available wraps, SF=styrofoam, FG=fiberglass, PS=polystyrene, PE=polyethylene, during a simulated freeze where temperature drops curvilinearly from 0° to -5° C in 8 hr, and windspeed is 0.5 $\pm$ 0.1 m s^{-1}.

temperature decreased in a curvilinear fashion from 0° to -5° C in 8 hr with light and variable windspeed (0.5 ± 0.1 m s^{-1}) (Fig. 7-4). In the case of the styrofoam wrap, the program had to be modified to account for freezing of water within the wrap, where it was assumed that the water would start to freeze at 0° C (no supercooling) and remain at that temperature until all the water was frozen. Results of the simulations generally agree with the α values in Table 7-1 in that predicted trunk temperatures are highest for styrofoam, intermediate for fiberglass, and lowest for polyethylene and polystyrene wraps.

Trunk temperature for the styrofoam wrap dropped to 1° C and remained constant, because during the simulation water inside the wrap began to freeze after 2 to 3 hr and a 1° C gradient was maintained across the airspace. However, trunk temperature under styrofoam wraps probably would drop to about 0° C instead of 1° C and remain constant (156), due to the rapid transfer of heat across the free airspace. It was not practical to account for convection currents in the airspace due to the excessively low time step (0.01 seconds) dictated by the high α of the airspace.

Trunk temperature for the polystyrene wrap was 1 to 2° C higher than air temperature throughout the simulation (Fig 7-4). This level of protection with polystyrene wraps is rarely observed in the field; normally these wraps provide no freeze protection whatsoever (68). Overestimation of trunk temperature with the polystyrene wrap may be due to underestimation of radiant heat loss from the wrap surface. There is no provision in the model for wrap surface temperature lower than air, because air temperature is used in the radiant heat transfer calculation (Equation 6-14) and consequently represents the lowest temperature that

can be achieved at the outer wrap surface. Additionally, the equation does not account for differences in emissivity among wraps. Polystyrene wraps are black, and have higher emissivities than the foil-faced fiberglass or light green styrofoam wraps (128).

The use of mean radiant temperature (MRT) instead of T_a in radiant heat transfer calculations and consideration of non-unit emissivity values may give more realistic prediction of trunk temperature with polystyrene wraps. The MRT is calculated from the Belding formula (10) after obtaining the globe thermometer temperature. A globe thermometer is an ordinary mercury in glass thermometer inserted into a 10 to 15-cm diameter blackened copper sphere. On a freeze night the globe thermometer temperature (and the MRT) would be below the air temperature due to radiant heat losses to its cooler surroundings (i.e., the sky and surface vegetation). For purposes of illustration, it was assumed that the globe thermometer temperature was 2° C below air temperature throughout the simulated freeze in Fig. 7-4. Simulations of fiberglass and polystyrene wraps were repeated using MRT in the radiant heat transfer equation, and emissivities of 0.09 and 1.0 for fiberglass and polystyrene, respectively (128). Predicted minimum trunk temperatures were unchanged from previous values for fiberglass wraps due to low emissivity, but were 0.9 °C lower for polystyrene wraps because the wrap surface was about 0.5° C lower than air temperature throughout the simulation (Table 7-3). Jackson et al. (68) measured trunk temperatures under polystyrene wraps in the field slightly lower than temperatures of unwrapped trunks, which may be explained by assuming that surface temperature of the polystyrene wraps was at the MRT and cooled the air inside the nearly airtight wrap below air temperature.

Table 7-3. Predicted minimum trunk temperatures for the 20-cm height for simulated freezes when air temperature decreases from 0° C to -5° C in 8 hr with windspeed of 0.5 ± 0.1 m s^{-1} using either air temperature (T_a) or mean radiant temperature (MRT) in calculation of radiant heat transfer.

Wrap type[z]	Variable in radiant heat transfer equation	Minimum trunk temperature (°C)[y]
Fiberglass	T_a	-2.2
	MRT	-2.2
Polystyrene	T_a	-3.6
	MRT	-4.5

[z] Emissivities were 0.09 and 1.00 for fiberglass and polystyrene, respectively.

[y] Each temperature is a single determination.

Use of MRT instead of T_a in radiant heat transfer calculations is advisable to avoid overestimation of surface temperature on freeze nights, especially for objects with high emissivity such as plant leaves or dark-colored objects. However, this calculation requires the globe thermometer temperature which is not readily available. Perhaps the temperature measured by a blackened thermocouple bead exposed to the sky could be used instead of the globe thermometer temperature.

That soil banks provide better freeze protection than wraps at the 20-cm height is undisputed. This is due in part to the lower thermal diffusivity of soil compared to wrap materials, and to the larger volume of a soil bank compared to the volume of a tree wrap. A comparison was made between soil and fiberglass wraps as insulative materials using the thermal properties of dry sand as the soil (57), the dimensions of a fiberglass wrap, and the same freeze conditions as in Fig. 7-4. The soil provided about 2° C more protection than a fiberglass wrap, but about 2° to 3° C less protection than a conventional soil bank provides at the 20-cm height (30) (Fig. 7-5). This suggests that superior freeze protection performance of soil banks is partially due to greater volume relative to a tree wrap.

Factors affecting the margin of protection provided by fiberglass tree wraps

Pattern and rate of air temperature decrease and freeze duration. Fiberglass wraps sometimes provide 4° C protection, yet on other occasions afford no protection at all. The pattern and rate of air temperature decrease and freeze duration can affect the margin of protection (difference between trunk and air temperature) observed with fiberglass or any tree wrap. Two patterns of air temperature decrease,

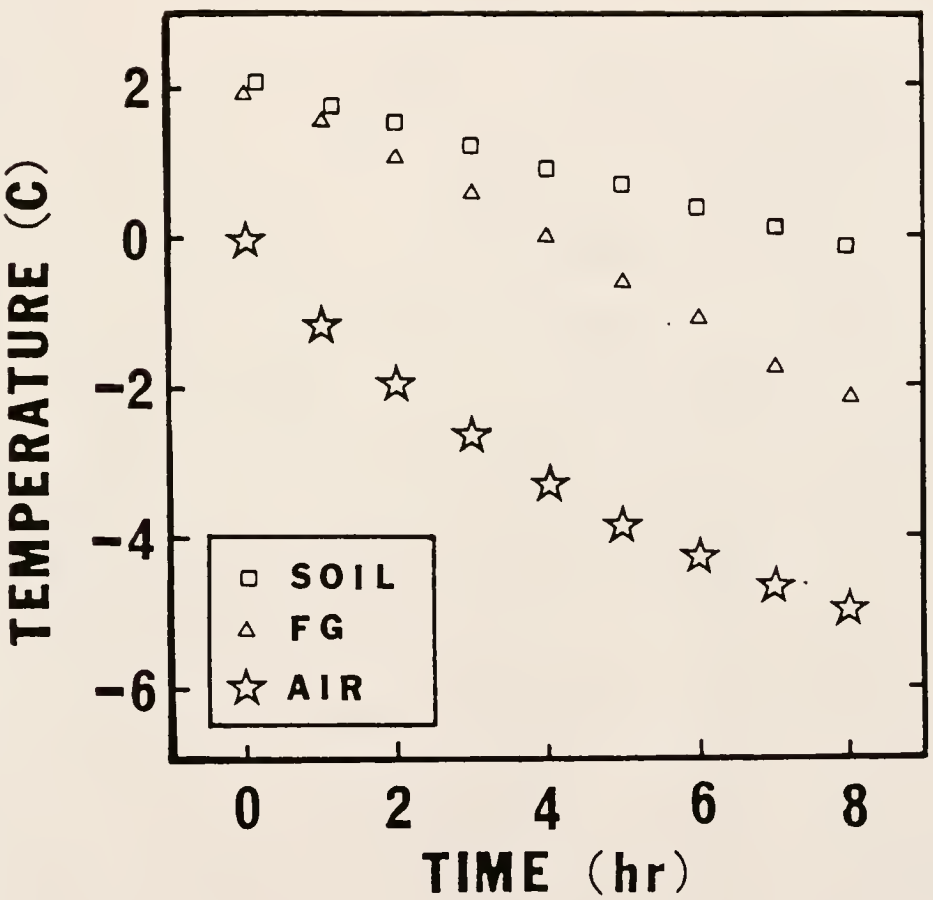


Fig. 7-5. Predicted trunk temperatures for air, a wrap with thermal properties of dry sand (SOIL), and a fiberglass wrap (FG). Freeze conditions are as in Fig. 7-4.

linear and exponential, were chosen for comparison at 3 minimum temperatures (Fig. 7-6). The average rates of air temperature decrease for both patterns are the same at a given minimum temperature because initial and final temperatures, and simulated time periods are the same for both patterns. However, when air temperature decreased exponentially toward a minimum, trunk temperature was lower than when air temperature decreased linearly toward the same minimum. Also, the margin of protection for the exponential pattern at 8 hr at all 3 minimum temperatures is greater than that at 12 hr. The opposite effect is seen for the linear pattern, where the margin of protection increases slightly with time due to lower rates of trunk temperature decrease than air. This indicated that freeze duration can affect margin of protection positively or negatively depending on pattern of air temperature decrease.

Longer durations below a given temperature occur with an exponential pattern than a linear pattern. Integrating over time, there is more area between 0° C and air temperature for the exponential than the linear pattern at the same minimum temperature. It seems that the minimum trunk temperature corresponds to the magnitude of the unit of integration ("freeze degree hr" ?) and not the minimum air temperature. It is better to express the intensity of a freeze using the integrated area below 0° C (or some other threshold temperature) along with minimum temperature rather than just minimum temperature alone.

The margin of protection increases at greater rates of air temperature decrease for both patterns of air temperature decrease, as seen by comparing margins of protection among average rates of air temperature decrease of -0.25°, -0.5° and -0.75° C hr^{-1} (Figs. 7-6a, b

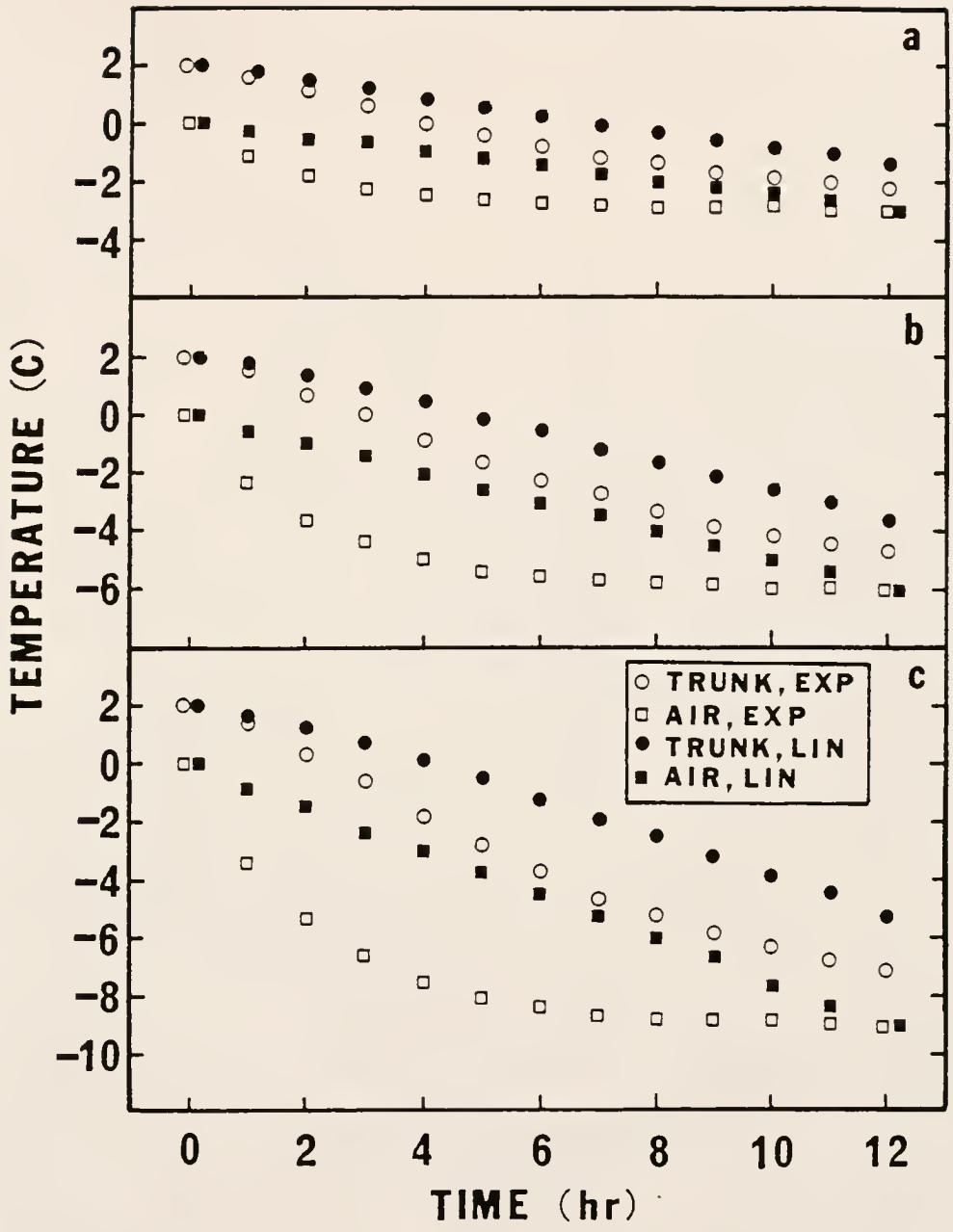


Fig. 7-6. Predicted trunk and air temperatures for young citrus trees with fiberglass wraps during 6 different simulated freezes. Minimum air temperatures and average rates of air temperature decrease are -3° C and -0.25° C hr^{-1} (a), -6° C and -0.5° C hr^{-1} (b), and -9° C and -0.75° C hr^{-1} (c) and windspeeds are 0.5 ± 0.1 m s^{-1}. Open symbols are for trunk (circles) and air (squares) temperatures during simulated freezes with exponential (EXP) patterns of air temperature decrease, and closed symbols are for trunk (circles) and air (squares) temperatures during simulated freezes with linear (LIN) patterns of air temperature decrease.

and c, respectively). Rose and Yelenosky (121) obtained similar results with fiberglass wraps that provided better protection at more rapid rates of air temperature decrease, particularly at lower heights on the trunk.

In field studies, margin of protection with fiberglass wraps was larger and increased throughout the night during the 20-21 Jan. 1985 freeze which had a rapid, linear pattern of temperature decrease, but margins of protection were small and decreased throughout the night on 21-22 Jan. 1985 when air temperature decreased in an exponential pattern (see Fig. 3-1). Thus, simulation output agreed qualitatively with field observations, and suggested that differences in margin of protection occurring under different freeze conditions may be due to the pattern and rate of air temperature decrease and freeze duration.

Trunk and wrap diameter. Increasing trunk and wrap diameter increased the simulated margin of protection provided by a fiberglass wrap (Fig. 7-7). Wrap diameter seems to have more of an influence on minimum trunk temperature than trunk diameter, suggesting that it is more important to increase the path length (wrap diameter) for thermal diffusion than to increase the amount of stored heat (trunk diameter) given these 2 alternatives, although an increase in both would have an additive effect. Young et al. (170) observed a nearly linear increase in minimum trunk temperature with increasing thickness of fiberglass wraps on 2 separate freeze nights. Differences in trunk and wrap diameter may be partially responsible for variations in the margin of protection observed with tree wraps in the field.

There is an upper limit of trunk diameter above which a decrease in trunk temperature could be expected due to decreased thickness of

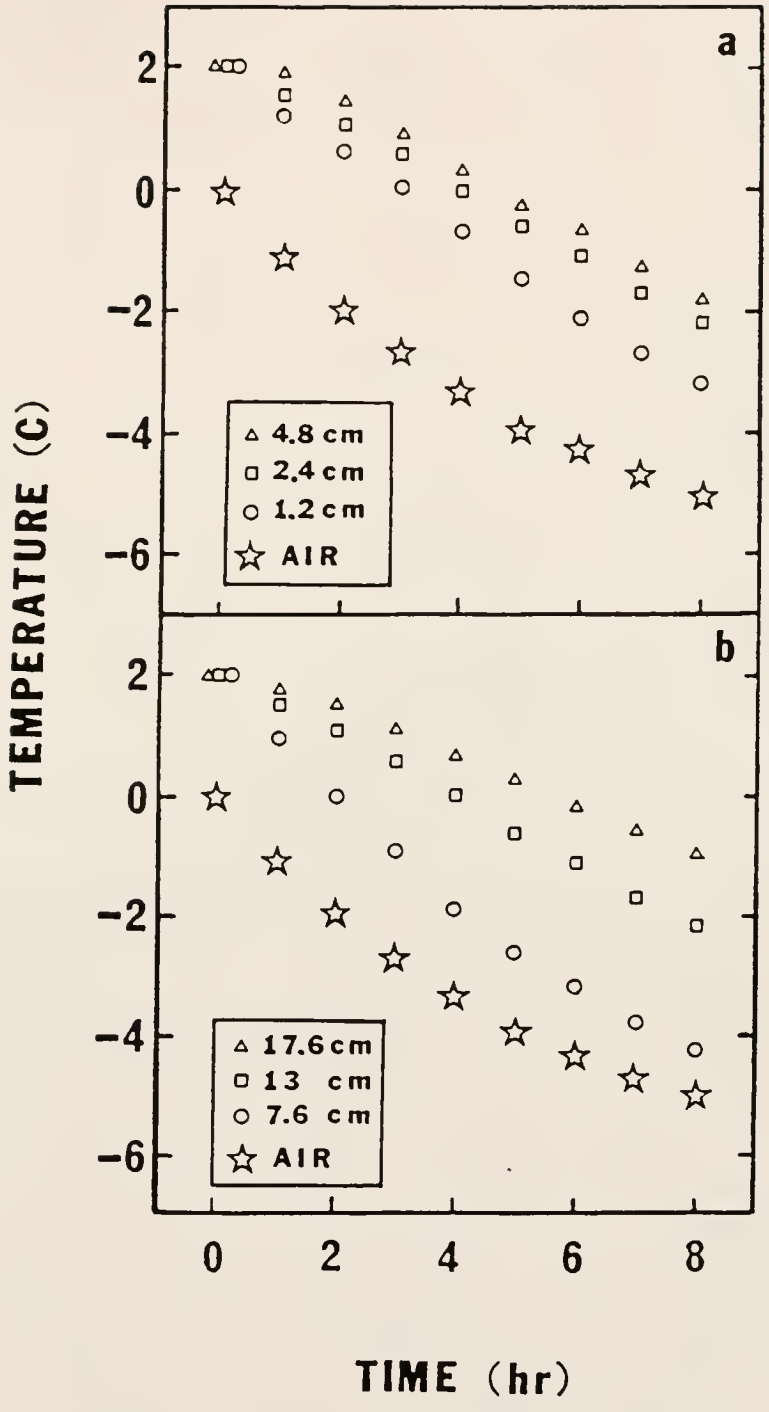


Fig. 7-7. Predicted trunk temperatures as affected by variations in trunk diameter with 13-cm diameter fiberglass wraps (a), and variations in wrap diameter with 2.4-cm diameter trunks (b). The values indicated in the lower left hand corner of (a) are trunk diameters, and those in (b) are wrap diameters. Freeze conditions are as in Fig. 7-4.

insulation as trunk diameter increases and wrap diameter remains constant. Therefore, it is important to avoid compression of fiberglass wraps during installation to achieve maximum wrap diameter, especially with older trees with relatively large diameters.

Effects of windspeed and soil temperature

Windspeed had a relatively minor influence on minimum trunk temperature, causing a decrease of only 0.4° C when windspeed increased from 0 to 5 m s-1 (Fig. 7-8). This was because wrap surface temperature was nearly equal to air temperature regardless of windspeed, and the trunk temperature of a wrapped tree is a function of wrap surface temperature and not windspeed or air temperature per se. A temperature difference of 0.4° C is below the sensitivity of thermocouples and the confidence limits of this simulation model. Furthermore, variations in windspeed are less likely to affect the margin of protection of tree wraps than variations in wrap and trunk diameter, rate and pattern of air temperature decrease, and freeze duration.

The influence of soil temperature on trunk temperature was investigated by running simulations using 3 different soil temperature regimes as follows: 1) decreasing from 2° to -6° C in 11 hr; 2) constant 5° C; 3) constant 10° C. Minimum trunk temperature at the 3-cm height increased substantially with soil temperature, although trunk temperatures at the 20- and 37-cm heights were unaffected by soil temperature regime (Table 7-4). This suggests that heat moving upward from the soil moves radially outward through the wrap before it can influence the temperature at the 20-cm or greater heights. Thus, heat added to the soil via irrigation water probably does not affect trunk temperature on freeze nights when irrigation is used for freeze protection.

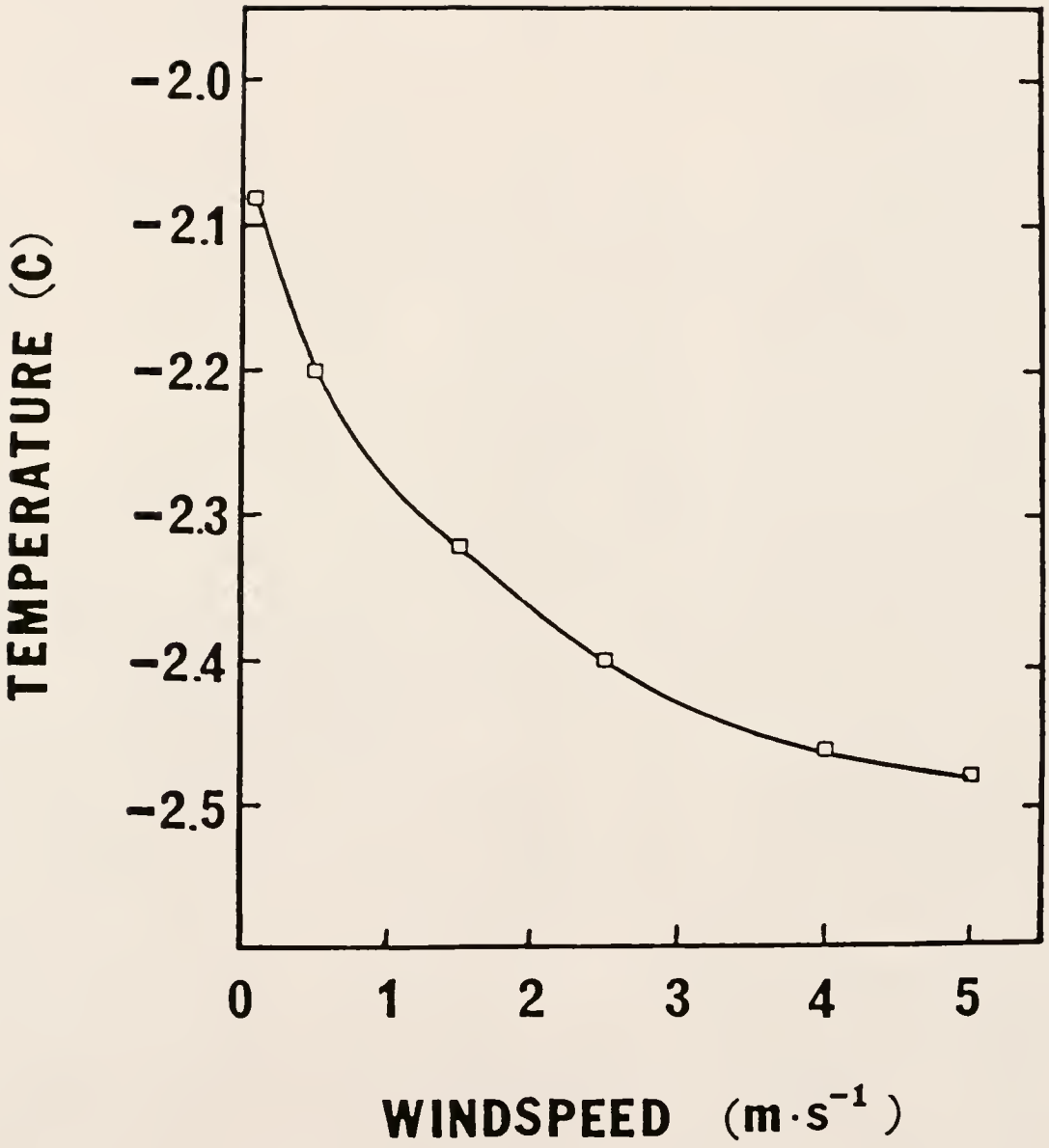


Fig. 7-8. Predicted minimum trunk temperatures of young citrus tree trunks under fiberglass wraps as influenced by windspeed when air temperature drops from 0° to -5° C in 8 hr.

Table 7-4. Simulated minimum trunk temperatures underneath fiberglass wraps at various heights from simulations using different soil temperature regimes and freeze conditions from 21 Jan. 1985.

Soil temperature regime	Minimum trunk temperature[z] (°C)		
	Height on trunk		
	3 cm	20 cm	37 cm
2° to -6° C in 11 hr	-5.4	-6.7	-10.4
Constant 5° C	2.1	-6.8	-10.7
Constant 10° C	6.1	-6.4	-10.7

[z] Each temperature is a single determination.

Conclusions

The level of freeze protection provided by a tree wrap was inversely related to the thermal diffusivity; i.e., a wrap with a lower α will provide more protection than one with higher α under similar freeze conditions. The heat transfer model of the tree wrap system predicted minimum trunk temperatures within 1 standard error of observed minimum trunk temperatures under a range of freeze conditions. However, predicted trunk temperature early in simulations usually was 1 to 2° C higher than observed trunk temperature. Less freeze protection can be expected with a given tree wrap when: air temperature decreases rapidly at first then remains nearly constant for the remainder of the night; rate of air temperature decrease is relatively low and freeze durations are relatively long; caliper of the tree is excessively low or high i.e, trees less than 1-year or greater than 3-years old; wraps are installed at diameters less than maximum. The ideal tree wrap would have low thermal diffusivity, the largest diameter economically feasible, lack free airspaces or ventilation holes, allow for gas exchange and trunk expansion, and last for 3 years without significant reduction in insulative capacity. Windspeed and soil temperature do not significantly affect temperature above the bud union of wrapped trees.

CHAPTER VIII
SIMULATION OF PROCESSES INVOLVED IN MICROSPRINKLER IRRIGATION FOR FREEZE PROTECTION OF YOUNG CITRUS TREES

Introduction

Microsprinkler irrigation is widely used in the Florida citrus industry for freeze protection of young trees (29). This system protects the lower 0.5 to 0.7 m of a young citrus tree even during severe advective freeze conditions (11, 30, 104). Tree wraps are often used in conjunction with microsprinkler irrigation for freeze protection because wrapped trunks intercept more irrigation water than bare trunks, and wraps provide additional trunk protection if the irrigation system fails during a freeze (30).

Guidelines for microsprinkler irrigation use on young trees have emerged from field studies (30, 104, Chapter III) and observations (103, 106). Current recommendations dictate that microsprinklers should be placed 0.3 to 0.8 m northwest of the tree because winds are normally from this direction during advective freezes (103). Trees irrigated from the downwind side or from distances > 1 m often sustain more damage than trees irrigated according to recommendations (104). Data from Chapter III demonstrate that a 90° spray pattern is superior to a 360° pattern, and irrigation rates as low as 22 liters hr^{-1} provide adequate trunk protection under advective freeze conditions. Use of relatively high irrigation rates (87 liters hr^{-1}) results in marginally better canopy protection than lower rates (38 liters hr^{-1}), but decreases the number of trees that can be irrigated during a freeze event due to

limitations on pumping capacity of irrigation systems. Low irrigation rates (<38 liters hr^{-1}) or intermittent sprinkling (32) may permit growers to irrigate larger acreages than currently possible on a given freeze night.

Investigators have speculated on the mechanisms of freeze protection with irrigation, often attributing trunk temperature elevation to latent heat of fusion of water (103, 104). Sensible heat transfer is assumed to be a negligible part of the microsprinkler irrigation process, a concept which has been carried over from models of overhead irrigation (104). However, trunk temperatures several degrees above 0° C frequently are observed during freeze events which cannot be explained by latent heat production alone. The effects of temperature, and interception and distribution of water on trunk temperature are unknown for microsprinkler irrigation, but these and other factors may have a substantial influence on freeze protection performance. More detailed information on the microsprinkler irrigation process is needed to assess the potential of higher risk techniques such as intermittent sprinkling and low (< 38 liters hr^{-1}) irrigation rates.

Modeling and simulation provide a means of analyzing the microsprinkler irrigation process in detail. Specific mechanisms can be addressed individually and their relative importance to the system as a whole evaluated. Simulation models of irrigation for freeze protection (46, 111) have been used to predict irrigation rates for canopy protection, but are not appropriate for studying trunk protection with the wrap/microsprinkler system. The simulation model described in Chapter VI was used in this chapter to analyze the microsprinkler irrigation process in the overall wrap/microsprinkler system. The

objective was to identify parameters of the irrigation process that influence trunk temperatures, and possibly suggest modifications in the system to maximize freeze protection performance.

Materials and Methods

The microsprinkler irrigation process was analyzed for wrapped trees only, because the wrap/microsprinkler combination provides advantages over either wraps or microsprinkler irrigation used alone (30) and wraps are often used in conjunction with microsprinkler irrigation by growers.

Due to the large number of parameters in the simulation model, values of several parameters were held at nominal values while others were changed in behavior analyses. Thermal properties of fiberglass tree wraps as determined in Chapter VII were used in all simulations. Trunk diameter was set at 2 cm for all simulations except validations for Jan. 1985 and Jan. 1987 where values from field measurements of 3 and 1 cm, respectively, were used. The following set of parameters describing the irrigation process were used as "standard" values in all simulations except where indicated otherwise: irrigation rate, 38 liters hr^{-1}; fraction of water intercepted by the wrap, 5%; water temperature, 12° C; percent coverage of the wrap surface with water (or ice), 70 %; the distribution of water around the wrap surface, as given in Fig. 6-4. Averages of field measurements, assumptions and calculations were used to arrive at "standard" values (see Chapter VI, section on parameters).

Validation

Trunk temperature data from field studies using young 'Hamlin' orange trees wrapped with fiberglass tree wraps during Jan. 1985 and Dec-Jan. 1985-86 were used for validation of the simulation model.

Conditions on these dates are described in detail in Chapter III. In addition, data from 2 freezes on 11-12 Jan. and 23-24 Jan. 1987 were used for validation; both freezes had minimum air temperatures of about -2.0° C, but the latter was a calm night while the former had windspeeds of about 2.5 m s^{-1}. Observed and predicted trunk temperatures correspond to the 20-cm height underneath fiberglass tree wraps in all cases. Freeze conditions (air temperature, windspeed, humidity) were approximated as closely as possible in simulations as linear, curvilinear or sinusoidal functions of time. Temperatures predicted within 1 standard error of observed means were considered valid.

During the 2 freezes of Jan. 1987, microsprinklers were carefully positioned to eliminate water from spraying into the canopy of trees. Trunk temperature changes as high as 6° C were observed on mild freeze nights due to water striking the canopy and then flowing down the trunk inside wraps. Repositioning microsprinklers eliminated this effect, and reduced variability in interception and percent coverage of the wrap surface by water. Values of fraction intercepted and percent coverage of the wrap surface were changed from "standard" conditions to 11% and 50%, respectively due to changes caused by repositioning the microsprinklers. Although the freezes in Jan. 1987 were mild and freeze protection was unnecessary for tree survival, validation on these dates was particularly important because values of percent coverage of the wrap surface and interception were known with much more confidence than on other dates used for validation. Furthermore, by eliminating water flowing down inside the wrap and resulting trunk temperature changes, deviations between predicted and observed trunk temperatures would be attributable solely to inaccuracies in the model.

Parameters Describing the Irrigation Process

Due to the stochastic nature of the 4 parameters describing the irrigation process, analyses were performed to assess potential changes in trunk temperature resulting from various levels of each parameter. Analysis was accomplished by varying one or more of the parameters at a time, and maintaining the others at "standard" levels. Two sets of freeze conditions were selected for these analyses: a severe advective freeze and a calm radiative freeze, which occurred on 20-21 Jan. 1985 and 26-27 Jan. 1985, respectively. Conditions from these dates represent the extremes of damaging freezes that occur in Florida, and are described in Chapter III.

The fraction of water intercepted was varied between 5 and 11% in increments of 2% in simulation analyses in order to span the range of measured values in the field. Water temperature was varied by $\pm$ 5° C of the mean value measured in the field, i.e., 7°, 12° and 17° C. The effect of percent coverage of the wrap surface was determined by simulation using values of 50, 70 and 90%, which also spanned the range of observed values in the field. The volume of water reaching the wrap surface opposite the microsprinkler was set at 10% of the fraction intercepted for both the 70% and 90% coverage simulations. Distribution of water on the wrap surface towards the microsprinkler was maintained as shown in Fig. 6-4, amounting to 100% of the fraction intercepted. The volume of water reaching the wrap surface away from the microsprinkler was specified at 5, 10, or 20% of the fraction intercepted. Thus, total amount of water on the wrap surface was either 105, 110 or 120% of the fraction intercepted, because the water reaching

the surface away from the microsprinkler was in addition to, and not taken from, the fraction intercepted.

Windspeed and Relative Humidity

The effects of windspeed and relative humidity on trunk temperature were simulated with the same 2 sets of freeze conditions used for analyzing the parameters describing the irrigation process. Simulations were run at windspeeds of 0, 1, 4.5, and 10 m s^{-1}, and relative humidities of 80 and 20%. During windspeed analyses, observed values of relative humidity were used, and during analyses of relative humidity, observed values of windspeed were used. The observed values of windspeed and relative humidity were, respectively: 4 $\pm$ 2 m s^{-1} and 50% decreasing to 25% on 20-21 Jan. 1985; 0 m s^{-1} and 50% increasing to 90% on 26-27 Jan. 1985.

Results and Discussion

Validation

Simulation of freezes of Jan. 1985

Predicted trunk temperature under the severe advective freeze conditions of 20-21 Jan. 1985 was similar to that observed early in simulations, but generally 2 to 3° C lower than observed means toward the end of the simulated time interval, regardless of irrigation rate (Figs. 8-1a, 8-2a, 8-3a). Discrepancies toward the end of the simulation may be explained by the freezing of water inside the wraps in the real system, which would maintain trunk temperatures around 0° C, and lack of account for this effect in the model system. Closer agreement occurred for all irrigation rates for the 26-27 Jan. 1985 freeze which was mild by comparison (Figs. 8-1b, 8-2b, 8-3b). The predicted values show the same rapid initial increase and subsequent

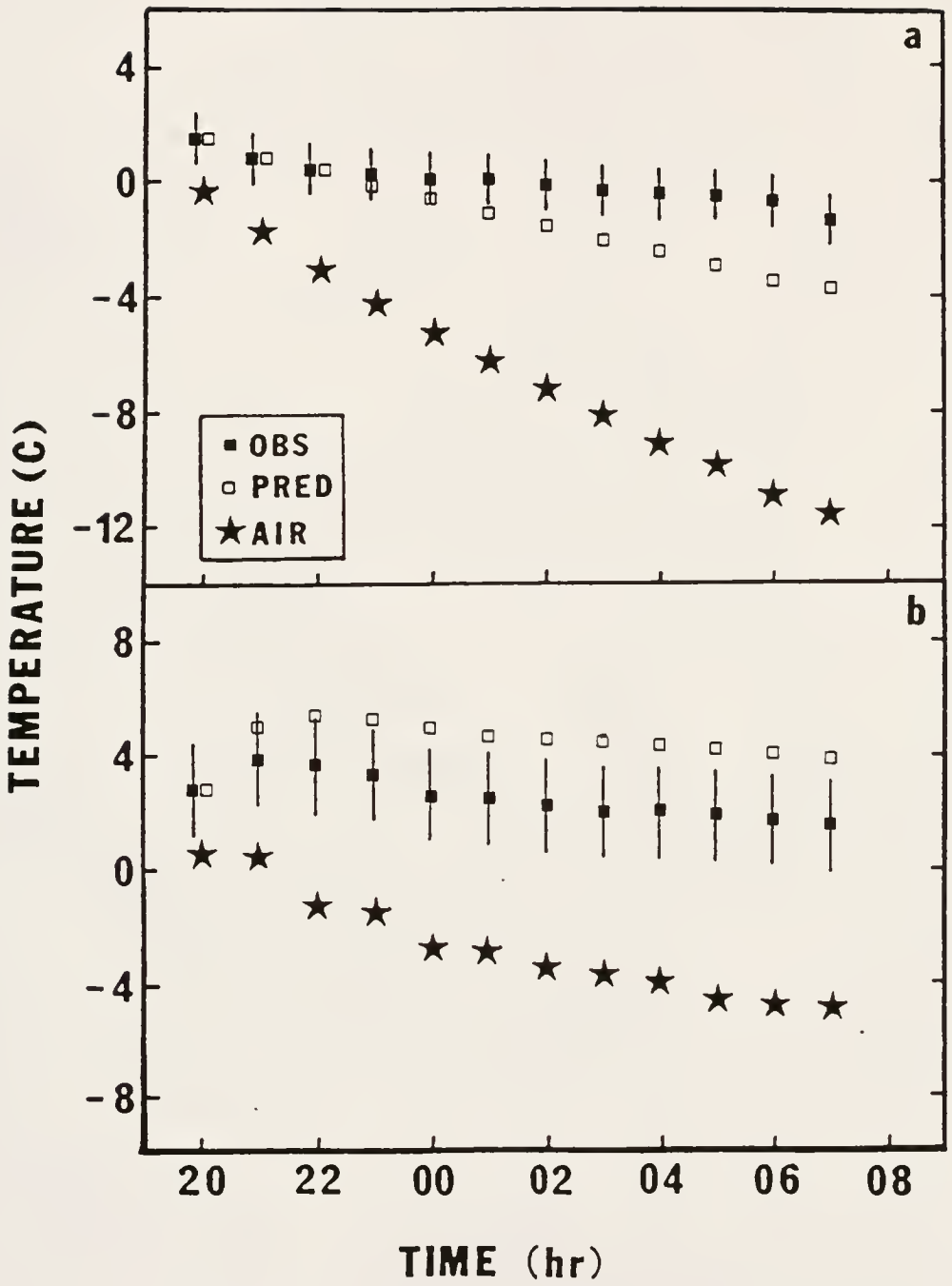


Fig. 8-1. Predicted (PRED) and observed (OBS) trunk temperatures at the 20-cm height and air temperatures (AIR) for 2-year-old 'Hamlin' orange trees wrapped with fiberglass tree wraps and irrigated with 38 liters hr^{-1} microsprinklers during an advective freeze on 20-21 Jan. 1985 (a) and a radiative freeze on 26-27 Jan. 1985 (b). Observed values are means $\pm$ SE, n=6.

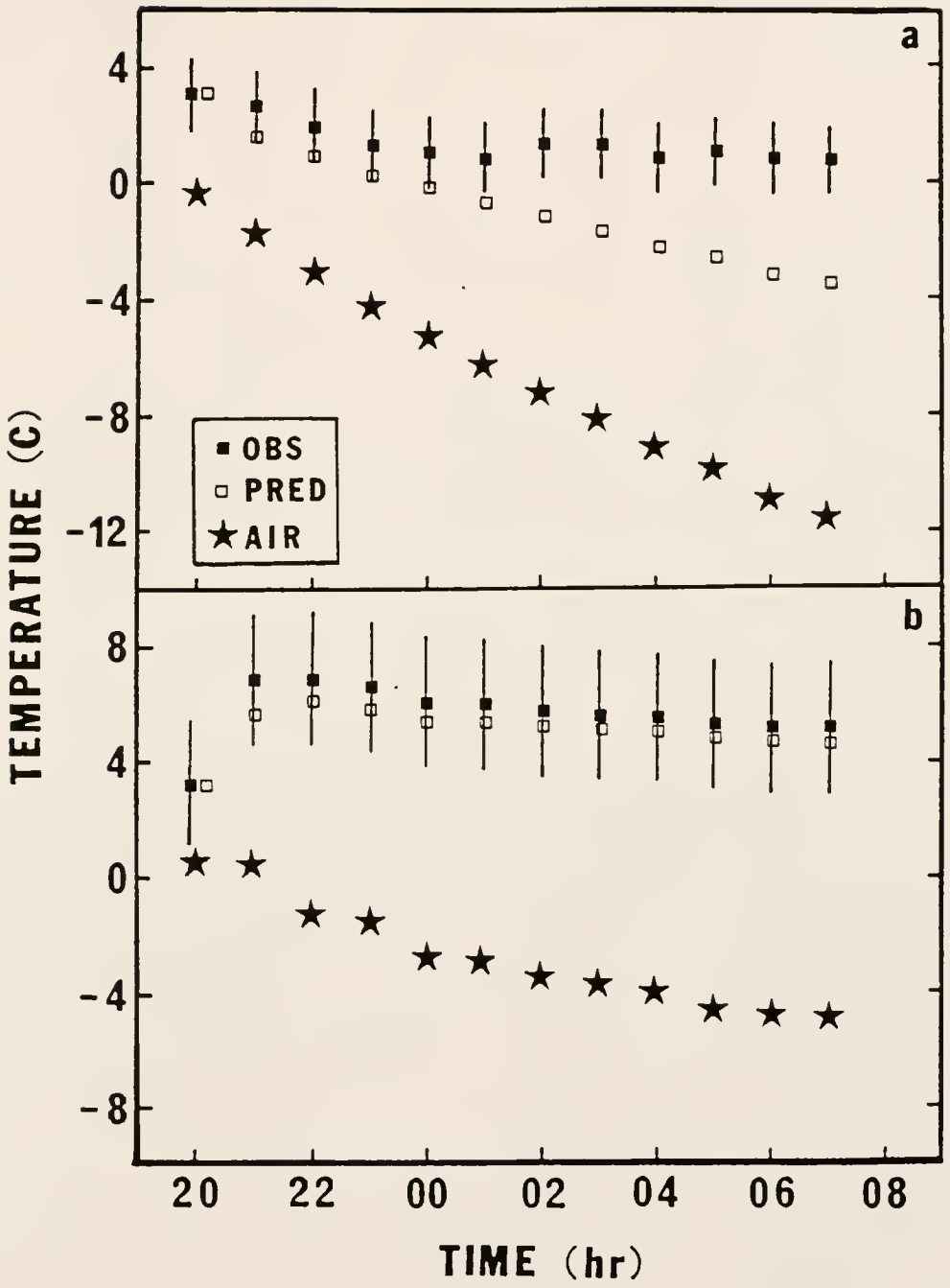


Fig. 8-2. Predicted (PRED) and observed (OBS) trunk temperatures at the 20-cm height and air temperatures (AIR) for 2-year-old 'Hamlin' orange trees wrapped with fiberglass tree wraps and irrigated with 57 liters hr^{-1} microsprinklers during an advective freeze on 20-21 Jan. 1985 (a) and a radiative freeze on 26-27 Jan. 1985 (b). Observed values are means $\pm$ SE, n=6.

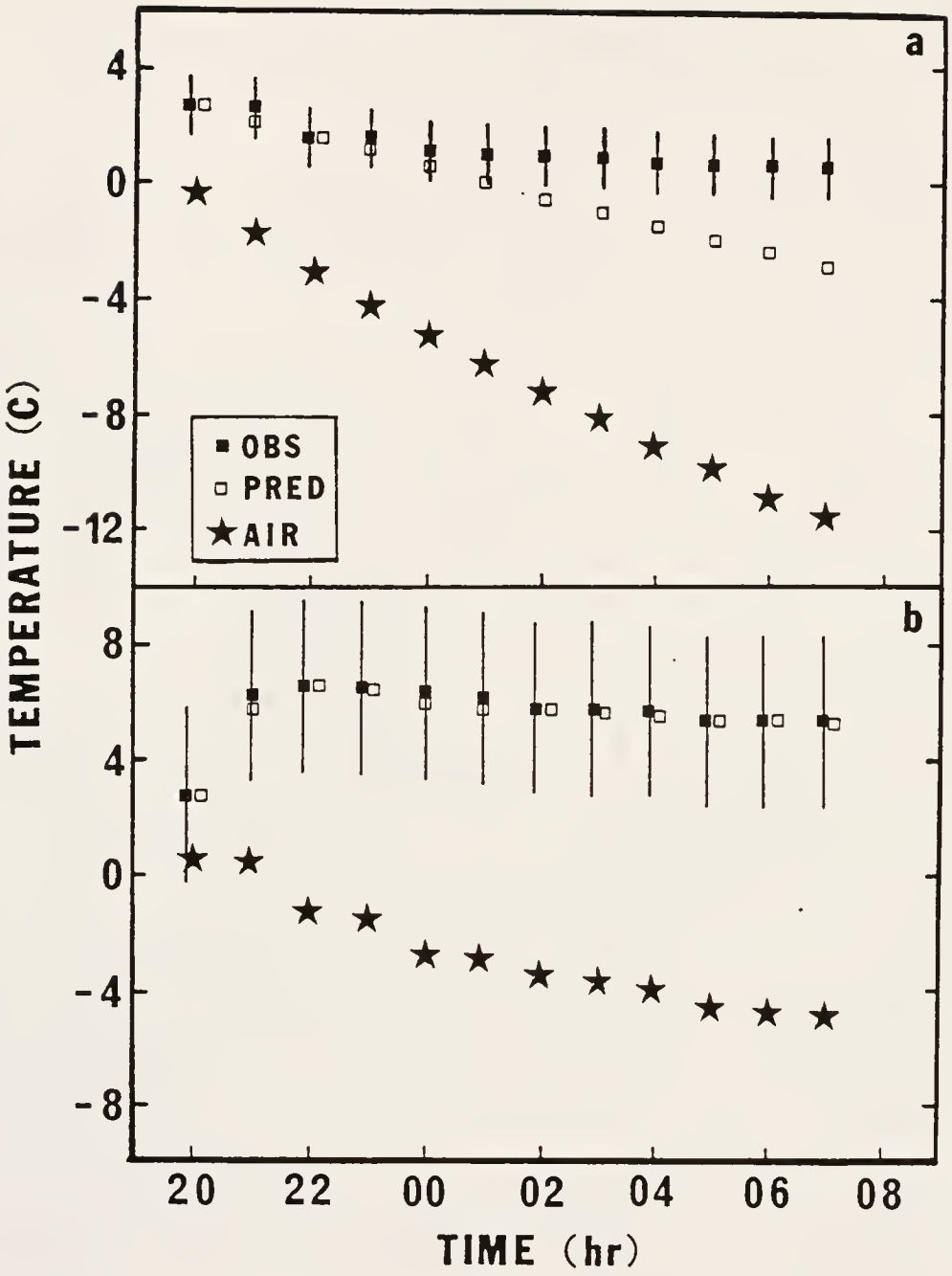


Fig. 8-3. Predicted (PRED) and observed (OBS) trunk temperatures at the 20-cm height and air temperatures (AIR) for 2-year-old 'Hamlin' orange trees wrapped with fiberglass tree wraps and irrigated with 87 liters hr^{-1} microsprinklers during an advective freeze on 20-20 Jan. 1985 (a) and a radiative freeze on 26-27 Jan. 1985 (b). Observed values are means $\pm$ SE, n=6.

slow decrease as the observed values for the 26-27 Jan. 1985 freeze, indicating that the model behavior is qualitatively similar to real system behavior under mild, "radiative" freeze conditions.

Simulation of freezes of Dec. and Jan. 1985-86

Predicted trunk temperatures generally were 1 to 3° C lower than those observed for all irrigation rates for the Dec.-Jan. 1985-86 simulations (Figs. 8-4, 8-5, 8-6), with the exception of the 22 liters hr^{-1} rate for the 26-27 Dec. 1985 freeze (Fig. 8-2b) where trunk temperatures were overpredicted by 1 to 2° C. However, the model behavior closely approximates that of the real system because both predicted and observed trunk temperatures remain relatively constant over time for all irrigation rates on all dates.

Simulation of freezes of Jan. 1987

The freezes of 11-12 and 23-24 Jan. 1987 provided the most rigorous test of the prediction capabilities of the simulation model, even though the freezes were extremely mild. As previously stated, parameters were known with more certainty and water was prohibited from entering the wrap on these dates due to positioning of the microsprinklers. However, predicted trunk temperatures still were 2 to 3° C below those observed on both dates (Fig. 8-7). Because no ice formed on the wrap surfaces on either of these dates, the simulation model underestimated the amount of sensible heat transfered from the irrigation water to the trunk, at least under mild freeze conditions. This is supported by validation on other dates where predicted trunk temperatures were generally 1 to 3° C lower than those observed.

The behavior of the model system approximated that of the real system on 23-24 Jan., but deviated substantially on 11-12 Jan. (Fig.

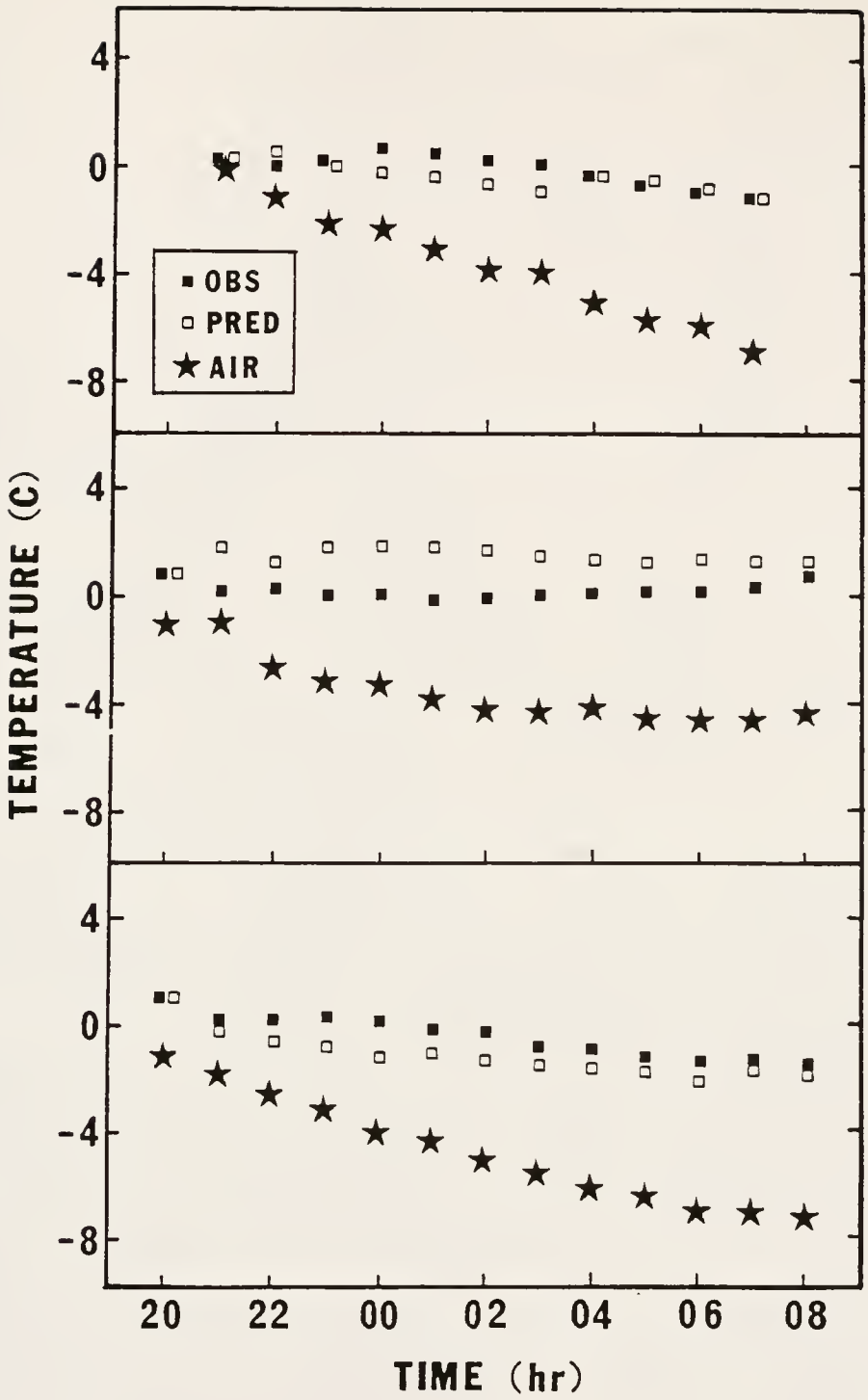


Fig. 8-4. Predicted (PRED) and observed (OBS) trunk temperatures at the 20-cm height and air temperatures (AIR) for 2-year-old 'Hamlin' orange trees wrapped with fiberglass tree wraps and irrigated with 22 liters hr^{-1} microsprinklers during advective freezes on 25-26 Dec. 1985 (a) and 27-28 Jan. 1986 (c), and a radiative freeze on 26-27 Dec. 1985 (b). Observed values are means $\pm$ SE, n=2. SE were smaller than the symbols, i.e., $< 0.4°$ C.

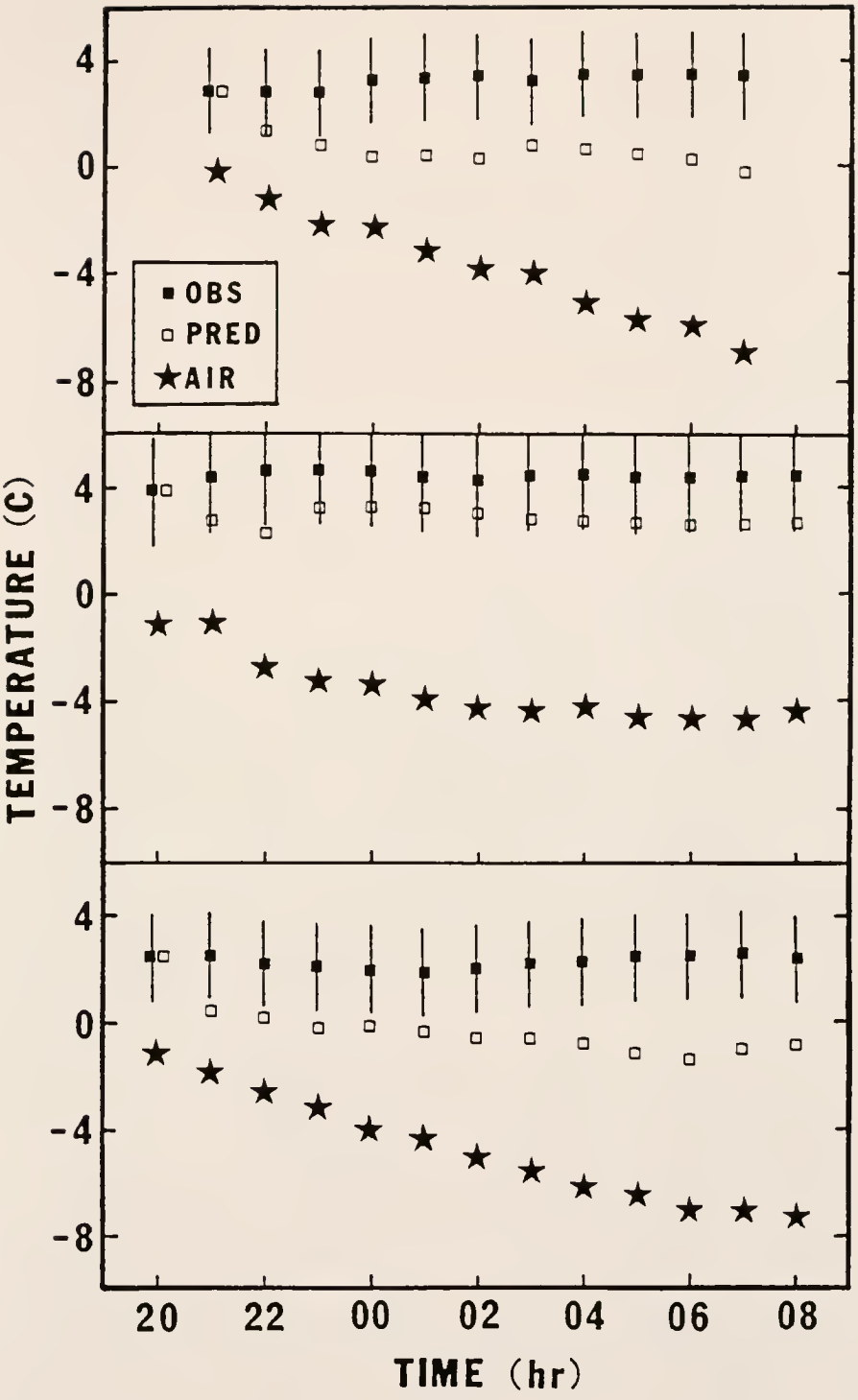


Fig. 8-5. Predicted (PRED) and observed (OBS) trunk temperatures at the 20-cm height and air temperatures (AIR) for 2-year-old 'Hamlin' orange trees wrapped with fiberglass tree wraps and irrigated with 38 liters hr^{-1} microsprinklers during advective freezes on 25-26 Dec. 1985 (a) and 27-28 Jan. 1986 (c), and a radiative freeze on 26-27 Dec. 1985 (b). Observed values are means $\pm$ SE, n=2.

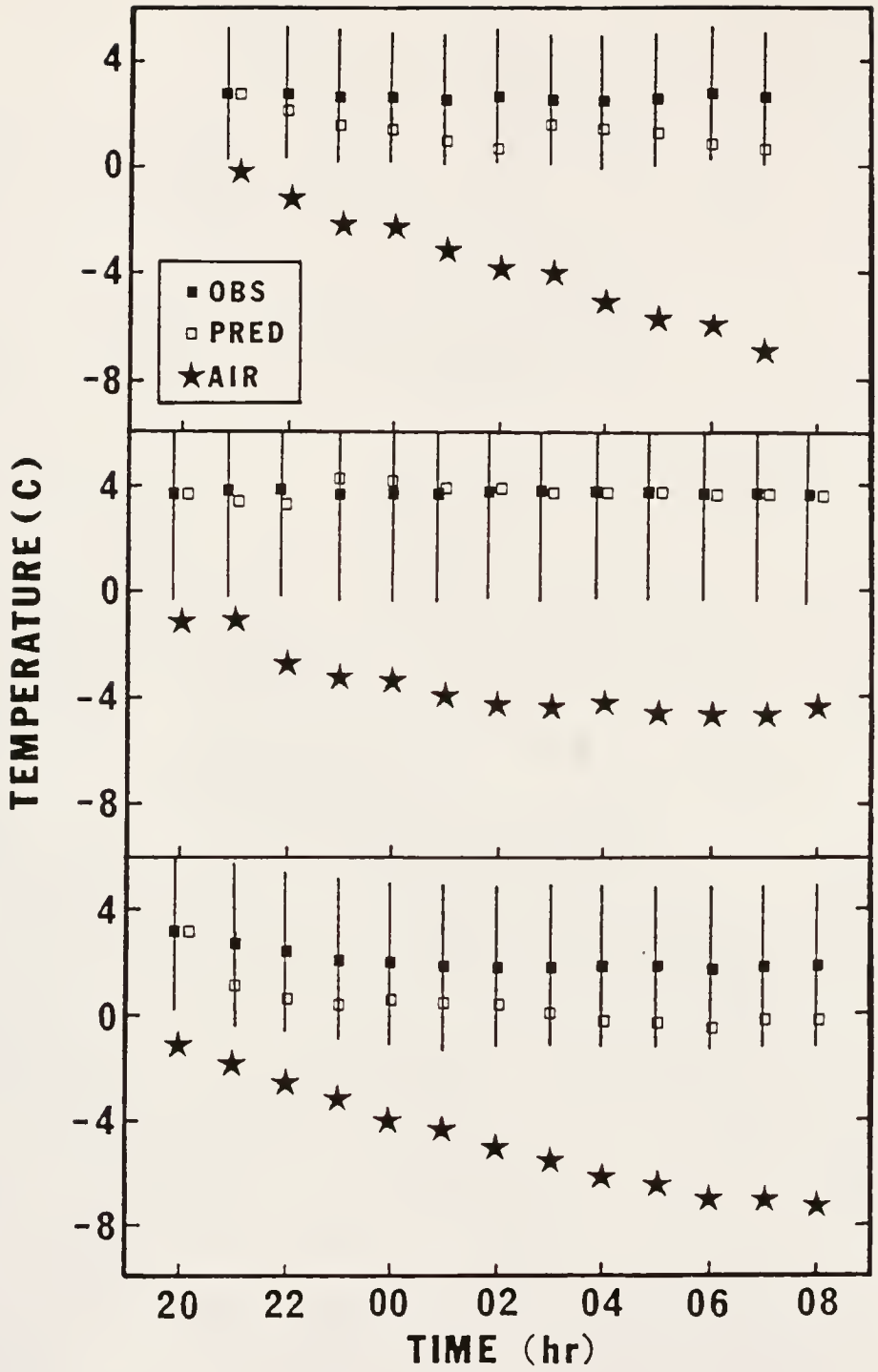


Fig. 8-6. Predicted (PRED) and observed (OBS) trunk temperatures at the 20-cm height and air temperatures (AIR) for 2-year-old 'Hamlin' orange trees wrapped with fiberglass tree wraps and irrigated with 57 liters hr^{-1} microsprinklers during advective freezes on 25-26 Dec. 1985 (a) and 27-28 Jan. 1986 (c), and a radiative freeze on 26-27 Dec. 1985 (b). Observed values are means $\pm$ SE, n=2.

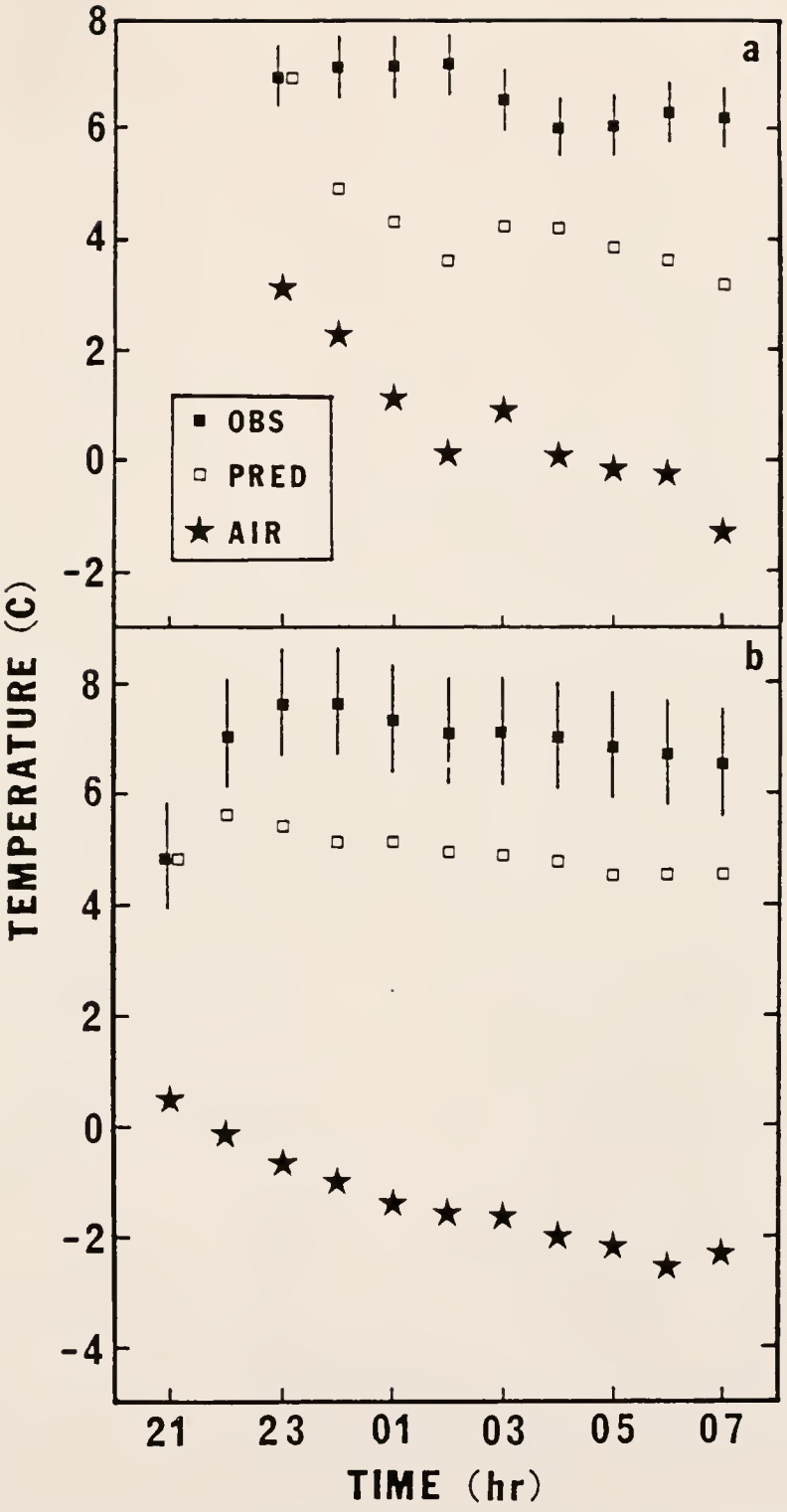


Fig. 8-7. Predicted (PRED) and observed (OBS) trunk temperatures at the 20-cm height and air temperatures (AIR) for 2-year-old 'Hamlin' orange trees wrapped with fiberglass tree wraps and irrigated with 38 liter hr^{-1} microsprinklers during mild freezes on 11-12 Jan. 1987 (a) and 23-24 Jan. 1987 (b). Observed values are means $\pm$ SE, n=6.

8-7). Predicted trunk temperatures follow the same general pattern as air temperature on 11-12 Jan., while the correlation between observed trunk and air temperatures is rather poor.

Ice accretion

The only other state variable in the simulation model aside from temperature was ice thickness. Ice accretion in the model system was qualitatively similar to that in the real system under severe advective freeze conditions because more ice accreted on the sides of the wrap than on the front or back, as observed in the field (Fig. 8-9). Non-uniform ice coverage results from uneven distribution of irrigation water around the wrap surface. Distribution is lowest on the sides, allowing ice to accrete rapidly there, and high enough on the wrap surface towards the microsprinkler to maintain temperatures above 0° C, prohibiting ice formation.

The quantity of ice predicted by the model was much lower than that observed in the field. This may be due to ice forming on the ground and accreting towards the wrap in the real system producing large ice masses, whereas the model system does not account for ice accretion other than that which occurs directly on the wrap surface. Differences in quantities of ice produced by the model and real systems is not thought to have an effect on trunk temperatures during constant irrigation because the temperature of a water-coated ice mass should be nearly 0° C regardless of its size.

Summary of model validation

Minimum predicted trunk temperatures were plotted against observed minima for all dates and irrigation rates from validation simulations in Figs. 8-1 to 8-7 (Fig. 8-8). Most of the data points lie below the 1:1

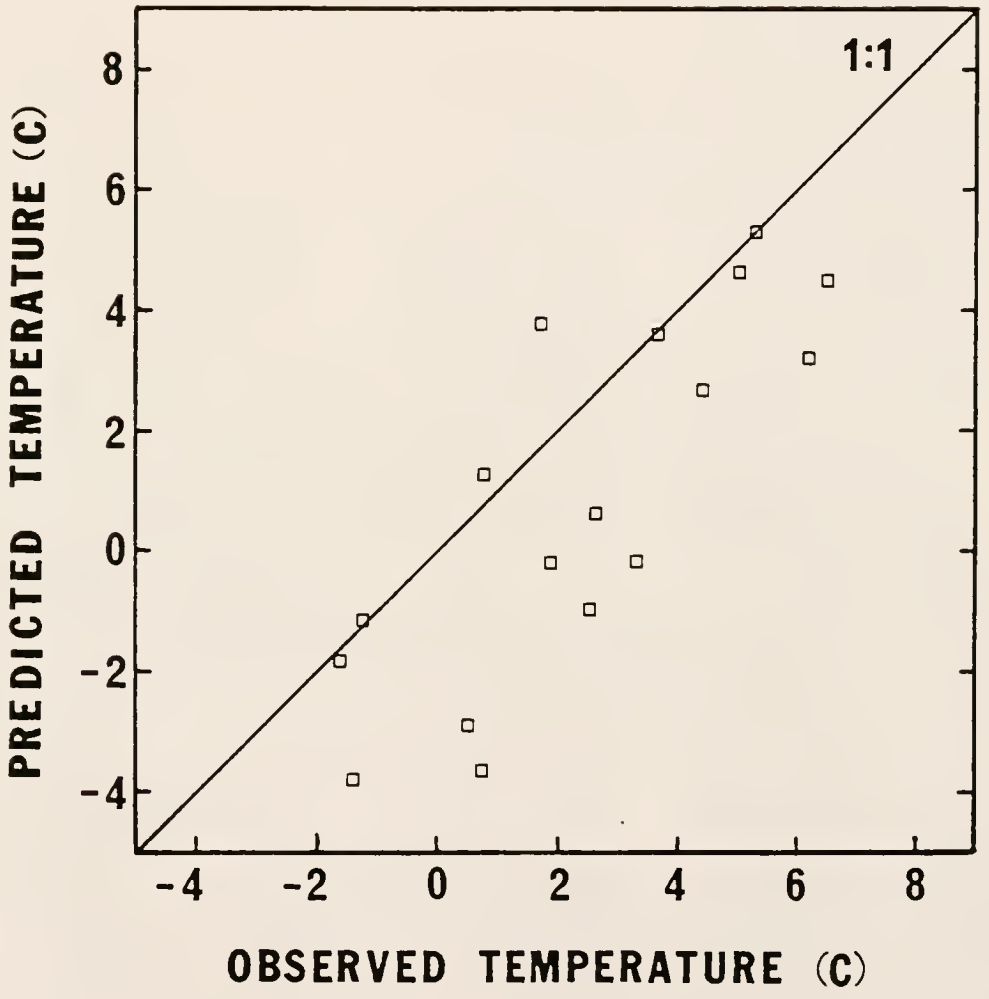


Fig. 8-8. Predicted minimum trunk temperatures plotted against those observed at the 20-cm height for all irrigation rates and dates used for validation. The solid line is a 1:1 correlation line with slope=1.0 and intercept=0.0. The linear regression equation is $y=-1.38 + 0.94x$, $r^2=0.65$.

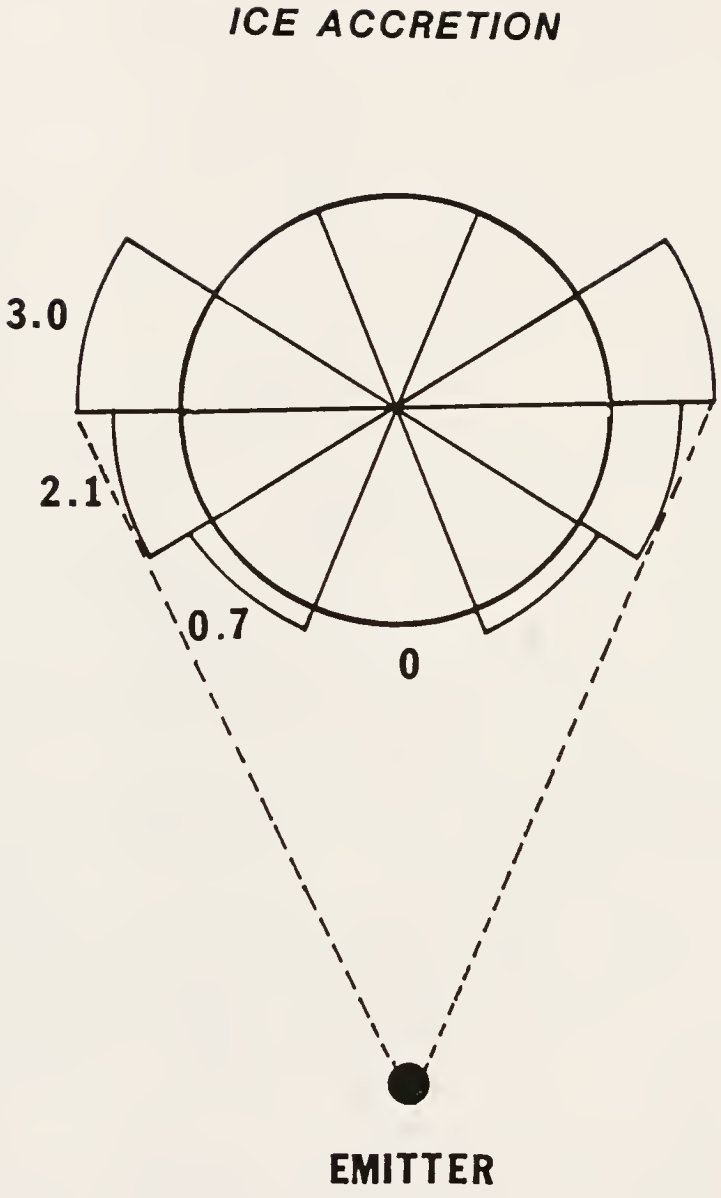


Fig. 8-9. Cross-section of a wrap showing the thickness of simulated ice on different regions of the wrap surface. Numbers indicate the ice thickness in cm for the adjacent region after 11 hr of irrigation with 38 liter hr^{-1} microsprinklers under simulated severe advective freeze conditions.

correlation line, reemphasizing that the model tends to underestimate the amount of heat added to the system by the irrigation process. Therefore, trunk temperature predictions by the model are conservative, and on average, about 1 to 3° C lower than those observed. Possible reasons for underprediction are discussed in the following sections where parameters describing the irrigation process, windspeed and relative humidity are analyzed.

Parameters Describing the Irrigation Process

Fraction of water intercepted

Increasing the fraction of water intercepted by the wrap resulted in increases in trunk temperature of about 0.25° C per each additional percent intercepted under both advective (Fig. 8-10a) and radiative freeze conditions (Fig. 8-10b). Higher fractions intercepted are obtained by positioning microsprinklers such that no water sprays over the top of the wrap, or by moving the microsprinklers closer to the tree. However, positioning microsprinklers in this manner to maximize interception results in a concomitant decrease in the percent of wrap surface covered with water, since water must be deflected from the canopy to reach the surface opposite the microsprinkler. The interaction between fraction intercepted and percent coverage will be addressed after discussion of the effects of the latter in another section.

Higher irrigation rates with lower fractions intercepted would result in the same volume of water per unit time reaching the wrap surface as lower irrigation rates with higher fractions intercepted. Therefore, use of more limited spray patterns with lower irrigation rates should result in the same level of protection as a wider spray

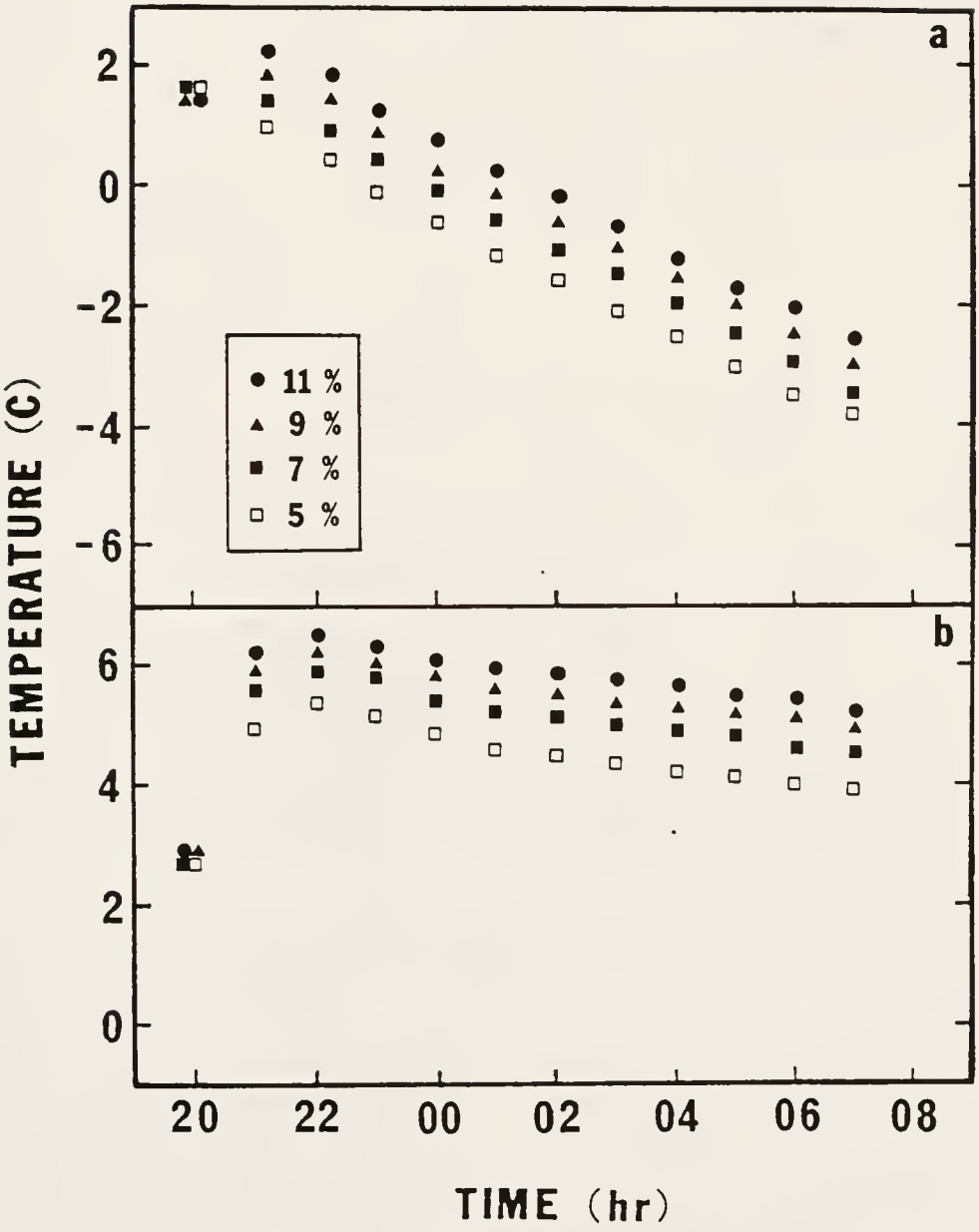


Fig. 8-10. Simulated temperatures at the 20-cm height for 2-cm-diameter citrus tree trunks with fiberglass tree wraps under severe advective (a) and radiative (b) freeze conditions. Simulations were run using different values of fraction of water intercepted by the wrap, indicated in the lower left corner of (a).

pattern used with a higher irrigation rate. This contention is supported by field studies using 90° vs. 360° spray patterns, where the 90° pattern provided superior freeze protection at all irrigation rates (Chapter III). More restricted spray patterns than 90° might allow use of low (< 38 liters hr^{-1}) irrigation rates for freeze protection, thus increasing the acreage that can be irrigated during a freeze event. However, such restricted spray patterns increase the risk of wind diverting irrigation water away from the tree, and may not be as reliable as the wider spray patterns. Furthermore, restricted spray patterns and low irrigation rates would be undesirable for water application on a routine basis due to more frequent clogging of emitters and reductions in wetted soil surface area.

Water temperature

Raising or lowering water temperature by 5° C from the mean value of 12° C changed trunk temperatures by about $\pm$ 1° C early in simulations of advective freeze conditions, but had little effect toward the end of the simulation (Fig. 8-11a). This was because ice formation occurred at all 3 water temperatures toward the end of the simulations, which invoked a boundary condition of 0° C at the ice-water interface. Hence, wrap surface temperatures were similar even though water temperature differed, and in the model system trunk temperatures respond to wrap surface temperatures, not environmental conditions per se. Under radiative conditions and in the absence of ice formation, water temperature is the major determinant of wrap surface temperature, and in turn, trunk temperature (Fig. 8-11b). Despite the substantial effect of water temperature on trunk temperature under radiative conditions, it does not appear that heating irrigation water would improve freeze

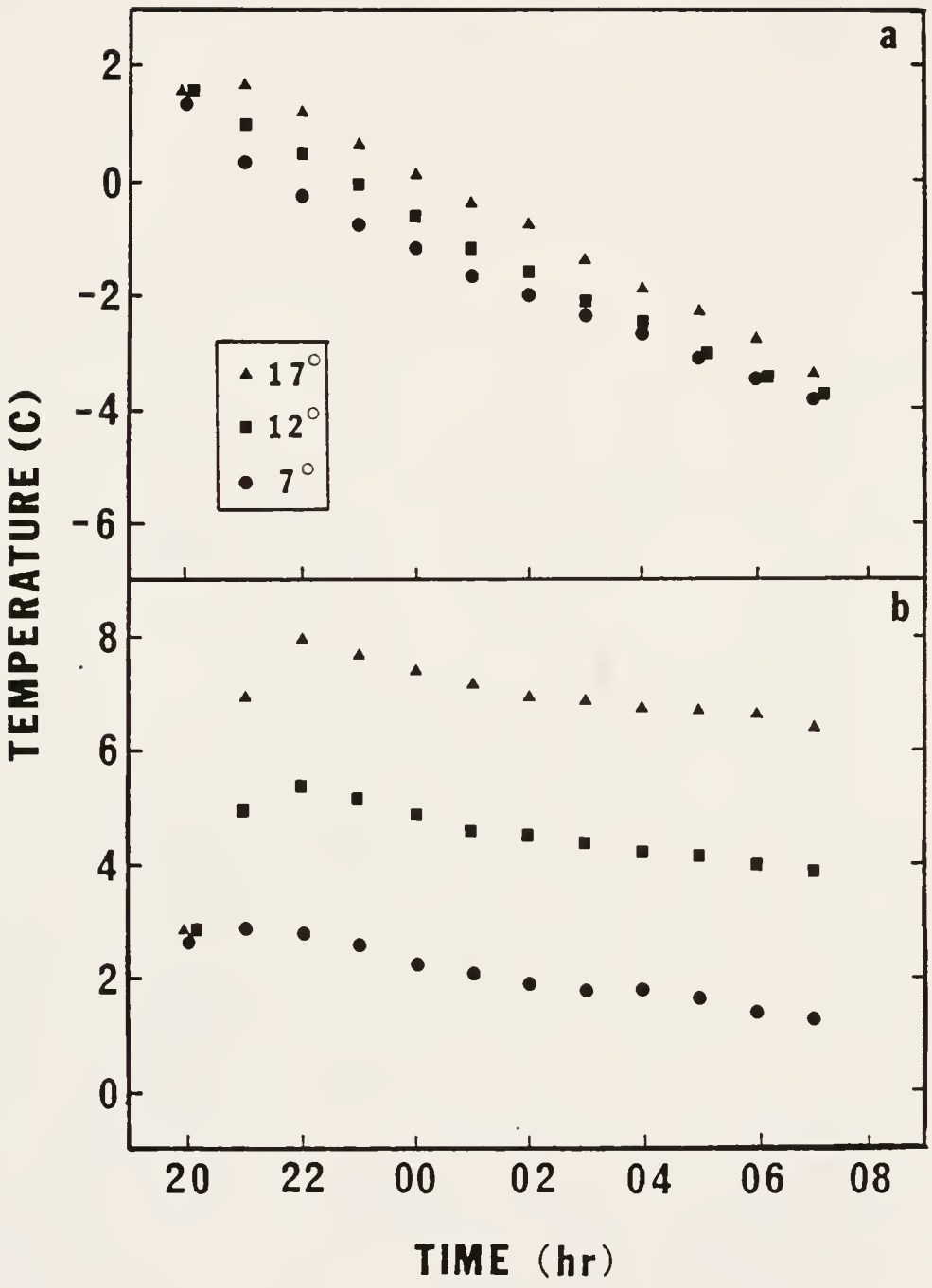


Fig. 8-11. Simulated temperatures at the 20-cm height for 2-cm-diameter citrus tree trunks with fiberglass tree wraps under severe advective (a) and radiative (b) freeze conditions. Simulations were run using different values of water temperature, indicated in the lower left corner of (a).

survival of young trees since even the 7° C water temperature maintained trunk temperatures above damaging levels under both radiative and advective freeze conditions.

Water striking the canopy and dripping onto the wrap would be expected to have a lower temperature than water directly intercepted. Thus, simulations were run where the water distributed on the wrap surface opposite the microsprinkler was 7° C, and water on the surface towards the microsprinkler was maintained at 12° C (data not shown). Under radiative conditions, lower water temperature on the surface opposite the microsprinkler reduced trunk temperatures 0.5° to 0.9° C compared to standard conditions where water was 12° C over the entire wrap surface. Trunk temperatures under advective conditions were unaffected by reduced water temperatures on the surface opposite the microsprinkler, as would be expected from data in Fig. 8-11a.

Unlike models of overhead irrigation for freeze protection (20, 46, 109, 114), sensible heat of the irrigation water is a major component responsible for the elevation of temperatures of plant parts in the simulation model of the wrap/microsprinkler system. This is probably due to shorter distances between sprinklers and trees in microsprinkler systems (1 m or less) than in overhead systems (several m) resulting in less cooling of the water as it travels through the air (46). Water arriving at leaf or stem surfaces from overhead sprinklers has a temperature of about 0° C regardless of its initial temperature (49); whereas, water from microsprinklers cools only about 5° C before it reaches the wrap or tree canopy (data not shown).

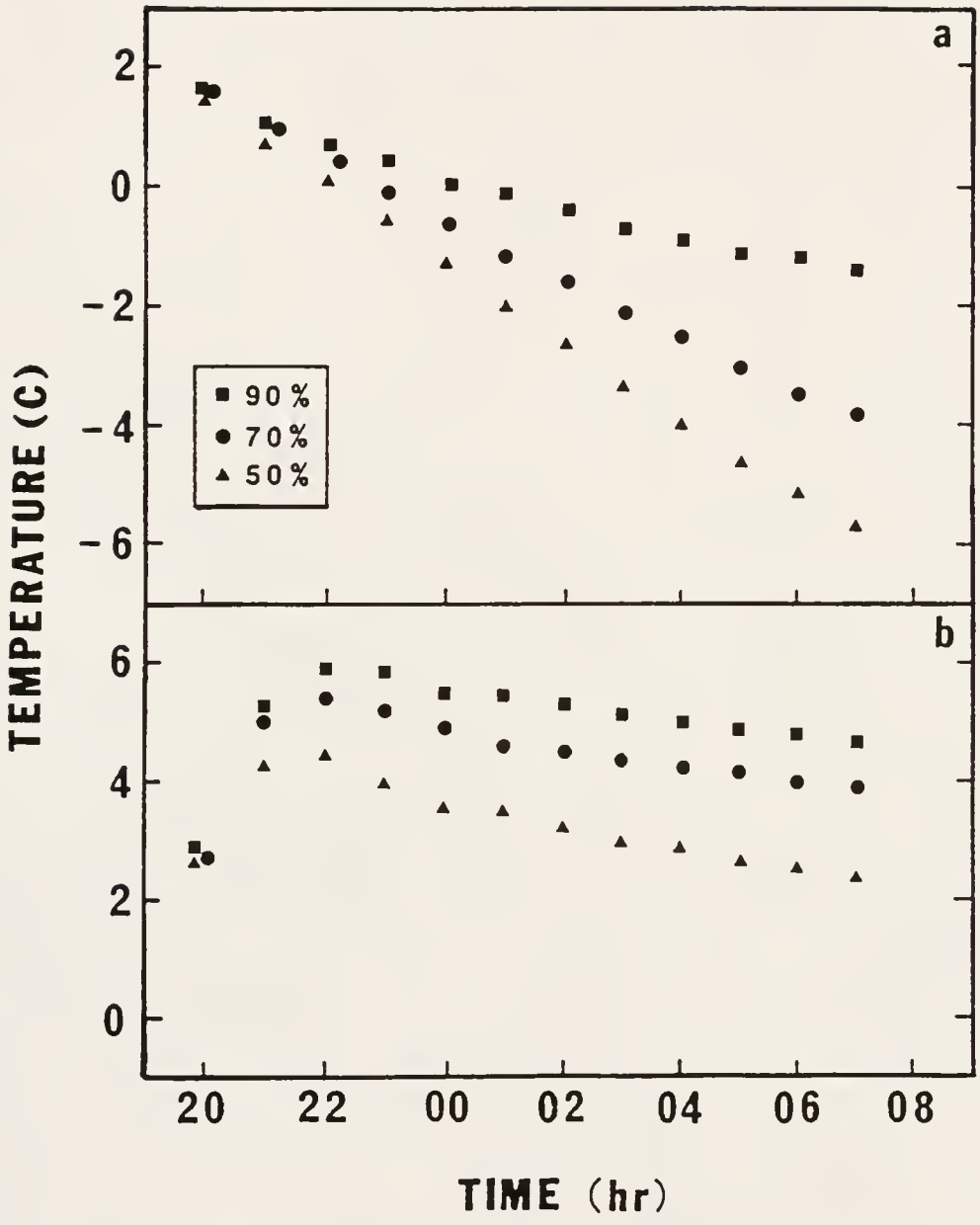


Fig. 8-12. Simulated temperatures at the 20-cm height for 2-cm-diameter citrus tree trunks with fiberglass tree wraps under severe advective (a) and radiative (b) freeze conditions. Simulations were run using different values of percent coverage of the wrap surface with water, indicated in the lower left corner of (a).

Percent coverage of the wrap surface with water

The percentage of the wrap surface covered by water (ice) greatly affected trunk temperatures, especially under advective freeze conditions (Fig. 8-12). Trunk temperature increased 4.5° and 2.5° C when percent coverage was increased from 50 to 90% under advective and radiative conditions, respectively. Differences in trunk temperatures between the 70% and 90% simulations suggest that spreading water over more area of the wrap surface opposite the microsprinkler is better than applying the same amount of water (10% of fraction intercepted) over a smaller area.

The magnitude of trunk temperature differences in Fig. 8-12 as compared to that in Fig. 8-10 suggests that microsprinklers should be positioned in order to maximize wrap surface coverage and not fraction intercepted. This is especially true under advective freeze conditions where differences in trunk temperature due to percent coverage were much greater than those due to fraction intercepted.

Distribution of water on the wrap surface

Trunk temperatures were unaffected under advective freeze conditions when the amount of water reaching the wrap surface opposite the microsprinkler was varied from 5 to 20% of the fraction intercepted (data not shown). However, under radiative conditions, trunk temperatures were 1° to 2° C higher when assuming 10 or 20% of the fraction intercepted reached the wrap surface opposite the microsprinkler as opposed to only 5%. Discrepancies between freeze conditions occurred because wrap surface temperatures opposite the microsprinkler were increased as the volume of water reaching this area increased under radiative conditions, causing the elevation in trunk

temperature. Conversely, ice accretion on the wrap surface opposite the microsprinkler occurred under advective freeze conditions regardless of volume applied, causing wrap surface temperatures to remain at about 0° C throughout the simulations.

Windspeed and Relative Humidity

Increasing windspeed from 0 to 10 m s^{-1} caused decreases in minimum trunk temperatures of about 5° C under simulated advective and radiative freeze conditions (Fig. 8-13). Relative humidity, however, had little or no affect on trunk temperatures at any time with the simulated air temperature and windspeed regimes of either set of freeze conditions (Fig. 8-14). Holding relative humidity constant as air temperature decreased caused dewpoint temperatures in simulations to decrease with time. Low dewpoint, or dry air, is often cited as a major factor limiting the use of irrigation for freeze protection (86, 104, 112). While this may be true for exposed plant tissues, data in Fig. 8-14 indicate that humidity is not a limiting factor for trunk protection of wrapped trees using microsprinkler irrigation. Windspeed on the other hand, is an extremely important consideration when using microsprinkler irrigation on wrapped trees, as it is with exposed plant tissues (20, 46, 109).

The data suggest that efforts to modify the microclimate of young citrus plantings should be directed at moderating windspeed rather than increasing relative humidity for best use of resources and labor.

Conclusions

The simulation model of the tree wrap/microsprinkler irrigation system consistently underestimated trunk temperature at the 20-cm height by 1 to 3° C, although the dynamic behavior of the model and real

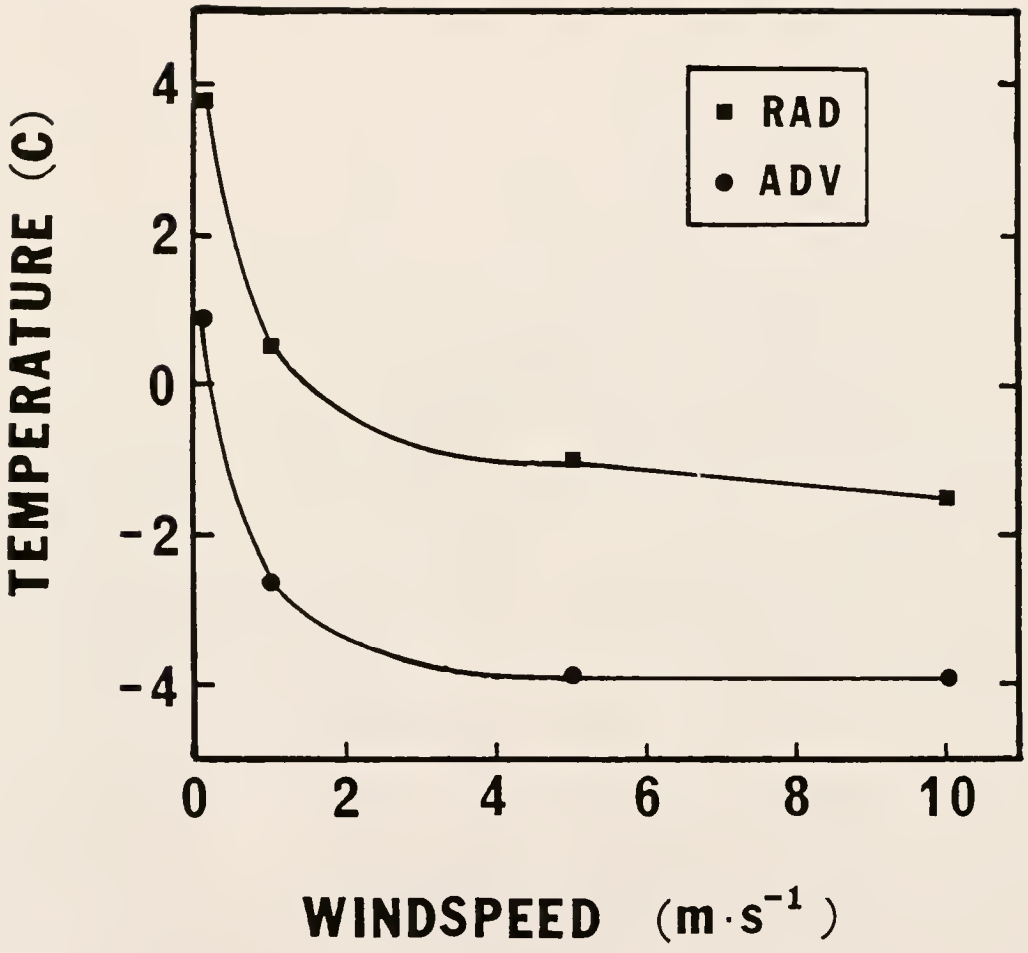


Fig. 8-13. Simulated minimum temperatures at the 20-cm height for 2-cm-diameter citrus tree trunks with fiberglass tree wraps under severe advective (ADV) and radiative (RAD) freeze conditions. Simulations were run at windspeeds of 0, 1, 4.5, and 10 m s-1.

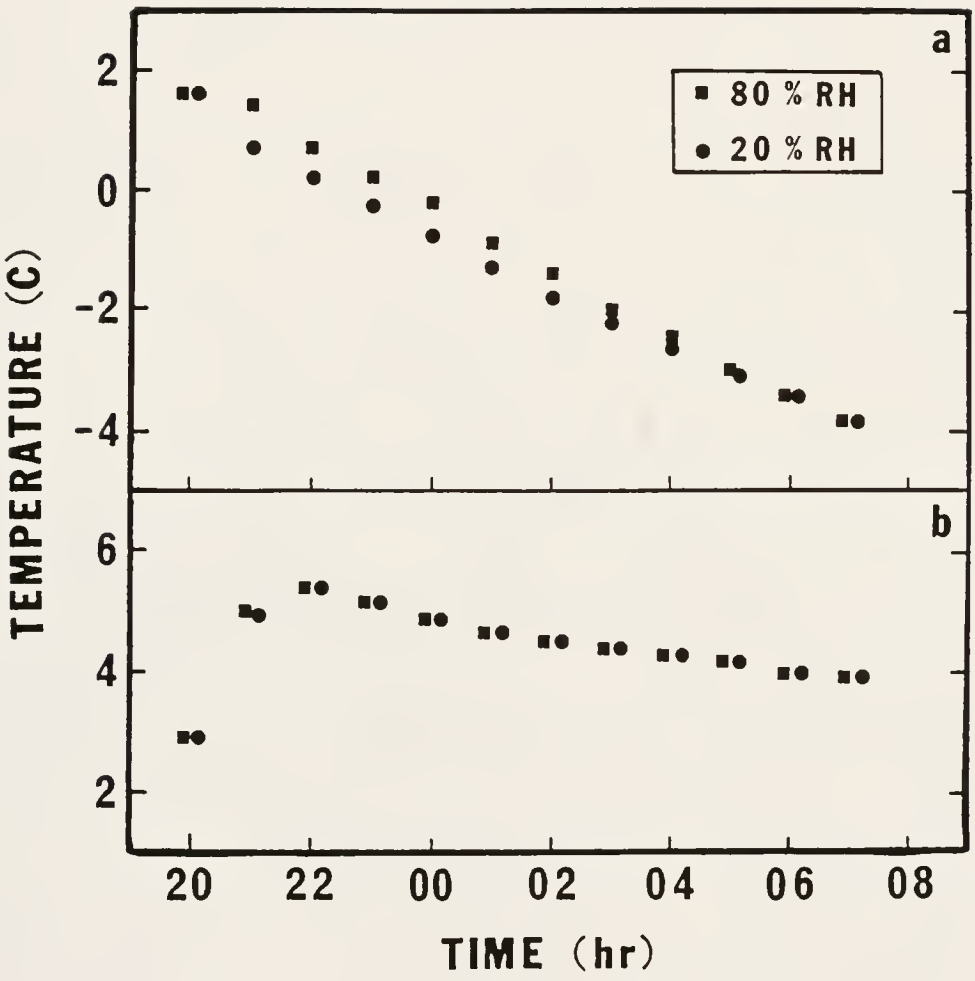


Fig. 8-14. Simulated trunk temperatures at the 20-cm height for 2-cm-diameter citrus tree trunks with fiberglass tree wraps under severe advective (a) and radiative (b) freeze conditions. Simulations were run using different values relative humidity, indicated in the upper right corner of (a).

systems were qualitatively similar. Sensible heat transfer from the irrigation water, although underestimated, was a major factor in the simulation model, unlike models of overhead irrigation. Although water temperature had a substantial influence on trunk temperature under radiative freeze conditions, increasing water temperature by 5° C did not alter minimum trunk temperature under advective freeze conditions. Microsprinklers should be positioned to maximize the percentage of wrap surface covered by water/ice, even though this would probably decrease the fraction of water intercepted. Windspeed influenced trunk temperatures to a much greater extent than relative humidity under advective and radiative freeze conditions.

CHAPTER IX
CONCLUSIONS

The overall purpose of this research was to study the freeze protection capabilities of the tree wrap/microsprinkler irrigation system for young citrus trees. Research can be classified into 2 main areas: applied field research (Chapters III through V), and more basic laboratory and computer simulation analyses (Chapters VI through VIII).

Field Research

Microsprinkler irrigation applied in a 90° pattern was superior to that applied in a 360° pattern with respect to elevation of trunk temperature, freeze survival and regrowth of young 'Hamlin' orange trees. A microsprinkler irrigation rate of 38 liters hr^{-1} applied in a 90° pattern provided the greatest increase in trunk temperature per unit water applied of all rates tested (0, 12, 22, 38, 57, and 87 liters hr^{-1}). Rates < 38 liters hr^{-1} provided 1° to 4° C additional trunk protection over fiberglass tree wraps alone and may allow larger acreages to be irrigated on a given night.

Microsprinkler irrigation did not increase air temperature, dewpoint, or net radiation above the wetted area of irrigated trees. Soil temperature was increased by irrigation rates > 38 liters hr^{-1} and reduced by rates < 38 liters hr^{-1} with respect to the unirrigated condition. However, simulation results suggested that a 5° to 10° C increase in soil temperature would not increase trunk temperatures at the 20-cm height. Therefore, most if not all of the increase in trunk

temperatures for irrigated trees results from release of sensible and latent heat of irrigation water directly, and not through microclimatic changes.

Freeze-damaged trees with wraps that excluded light entirely had lower numbers and dry weights of trunk sprouts than trees with wraps that allowed some light to reach the trunk. Therefore, opaque or dark-colored wraps which exclude light are probably best for trunk sprout inhibition. Alternatively, wraps should be removed from trees killed to the top of the wrap in order to encourage development of trunk sprouts and reestabishment of the canopy.

Laboratory and Computer Simulation Studies

Thermal diffusivity of various tree wraps was indicative of their freeze protection capability. Therefore, materials with low thermal diffusivity which are durable and inexpensive would make good tree wraps with respect to freeze protection.

Less freeze protection can be expected with a given tree wrap under the following conditions: air temperature decreases rapidly at first then remains constant the remainder of the night; rate of air temperature decrease is relatively low and freeze duration is relatively long; wrap diameter is less than optimum due to improper installation or weathering; trunk caliper is particularly low (< 1 cm) or high (> 5 cm).

Microsprinklers should be positioned to maximize the percentage of wrap surface covered by water/ice, although this would probably decrease the fraction of water intercepted. The potential exists to use irrigation rates of about 4 liters hr^{-1} for freeze protection because wrapped trunks intercept only 5 to 11% of the water applied from 38 liter hr^{-1} emitters, and water that misses the wrapped trunk does not

indirectly influence trunk temperature. Water temperatures of 7° and 17° C provided essentially the same level of protection in simulations of severe advective freezes. However, water temperature had a substantial influence on trunk temperature under radiative freeze conditions or in the absence of a simulated ice layer. Windspeed had a much greater influence on trunk temperature than relative humidity. Therefore, efforts to modify the microclimate of young citrus trees should be directed at reducing windspeed rather than increasing relative humidity for best use of resources and labor.

APPENDIX A

The following is a listing of the 2-D tree wrap simulation code in FORTRAN, which begins with a list of variables used throughout the program. The 1-D program was similar, lacking terms and the loop for vertical heat transfer.

```
C       MARK RIEGER
C       WRAP2D.FOR   VERT. HEAT FLUX TRUNK WRAP SIMULATION
C
C       VARIABLES:
C       AMP=AMPLITUDE OF EXPON. TEMP. DECREASE FN
C       AREA=SURFACE AREA OF WRAP (CM2)
C       CPA=SPECIFIC HEAT OF AIR (CAL/KG*K)
C       CPB=    "           " BARK    "
C       CPW=    "           " WRAP    "
C       CV=RATE OF CONVECTIVE HEAT LOSS(CAL/S)
C       D=CHARACTERISTIC DIMENSION (CM)
C       DT=DELTA T
C       DTDT=TIME RATE OF CHANGE IN TEMP (°C/S)
C       DTSOIL=TIME RATE OF CHANGE OF SOIL TEMP (°C/S)
C       DR=RADIAL DISTANCE INCREMENT (CM)
C       DZ=VERTICAL DISTANCE INCREMENT (CM)
C       EMIS=EMISSIVITY OF WRAP SURFACE
C       G=HEAT CONDUCTION THRU OUTERMOST WRAP LAYER (CAL/CM2 S)
C       GRAD=GRADIENT IN TEMP. THRU WRAP
C       HC=CONVECTIVE HEAT TRANSFER COEF. (CAL/CM2 S K)
C       KA=THERMAL CONDUCTIVITY AIR(CAL/S CM K)
C       KB=  "          "       BARK
C       KW=  "          "       WRAP
C       MID=MIDPOINT BETWEEN SOIL AND TOP OF WRAP
C       NU=NUSSELT NUMBER
C       PI=3.141592654
C       PR=PRANDTL NUMBER
C       R=RADIATIVE HEAT TRANSFER FROM WATER/ICE(CAL/S)
C       RDS=RADIUS # (ITERATION)
C       RE=REYNOLDS NUMBER (V*D/U)
C       RH=RELATIVE HUMIDITY
C       RHOA=DENSITY OF AIR (KG/CM3)
C       RHOW=  "        WRAP    "
C       RHOB=  "        BARK    "
C       RWRAP= "                    WRAP
C       RBARK=  "                   BARK
C       SBC=STEFAN-BOLTZMANN CONSTANT(1.355E-12CAL/CM2 S K4)
C       ST=STOP TIME
C       T=TEMP. IN °K
C       TA=TEMPERATURE OF AIR (K)
C       TAMIN=MINIMUM AIR TEMP
```

```
C        TCA=TEMP. IN °C
C        TIME=TIME (SEC)
C        TO=STARTING TIME
C        TOP=HEIGHT OF TOP OF WRAP (CM)
C        TSOIL=TEMPERATURE OF THE SOIL SURFACE (°K)
C        TSOILI=INITIAL "    "    "   "   "        "
C        TAU= K IN EXPON. TEMP DECREASE
C        U=KINEMATIC VISCOSITY AIR (CM2/S)
C        V=WIND VELOCITY (CM/S)
C        VAMP=AMPLITUDE OF WINDSPEED FLUCTUATION (CM/S)
C        VERT=# OF ITERATIONS OF VERTICAL DIMENSION (TOP/DZ)
C        VXBAR=MEAN WINDSPEED (CM/S)
C
C
C        DECLARATIONS ETC.
C
      REAL AMP,CP,CPA,CPB,CPW,CV
      REAL D,DR,DTDT(50,40),DZ,EMIS,G,GRAD
      REAL HC,K,KA,KB,KBLONG,KW,NU,PI,PR
      REAL R,RDS,RE,RHO,RHOA,RHOB,RHOW
      REAL RBARK,RWRAP,SBC,TA,T(50,40),TSOIL,TSOILI
      REAL TC(50,40),TAMIN,TAU,U,V,VAMP,VXBAR,XMAX
      REAL TIME,TO,ST,DT,VERT,MID,TOP,DTSOIL,X
      INTEGER INT
      OPEN(UNIT=50,FILE='WRAP3D.DAT',STATUS='OLD')
      OPEN(UNIT=51,FILE='WRAP3D.OUT',STATUS='NEW')
      READ(50,*) TO,ST,DT,AMP,TAU,TAMIN,V,VAMP,VXBAR
     +,RWRAP,RBARK,GRAD,EMIS,KW,RHOW,CPW,
     +KB,RHOB,CPB,TSOILI,DTSOIL,D,DR,DZ,TOP
      CPA=241.9
      KA=0.0000578
      KBLONG=0.00142
      PI=3.141592654
      RDS=RWRAP
      RHOA=0.000001304
      SBC=1.355E-12
      TIME=0
      TA=273.
      TCA=0.
      TSOIL=TSOILI
      U=0.133
C
C     INITIALIZE TEMPS TO STARTING VALUES (2 C GRADIENT THRU WRAP)
C
      DO 10 J=2,TOP-1
      DO 20 I=1,RWRAP
         TC(I,J)=GRAD-((GRAD/RWRAP)*I)
         TC(I,1)=TSOIL
         TC(I,TOP)=TA
         T(I,J)=TC(I,J)+273.
20    CONTINUE
10    CONTINUE
C
C     OUTPUT HEADINGS
```

```
C
      WRITE(51,700)KW,RHOW,CPW,KB,RHOB,CPB,RWRAP,RBARK,VXBAR
700   FORMAT(' ',15X,'WRAP3D SIMULATION OUTPUT',//,6X,
     +'KW= ',F10.8,2X,'RHOW= ',F10.8,2X,'CPW= ',F5.1,/,
     +6X,'KB= ',F10.8,2X,'RHOB= ',F10.8,2X,'CPB= ',F5.1,/,
     +6X,'WRAP RADIUS(5mm)= ',F4.1,2X,'TRUNK RADIUS(5mm)= ',F4.1,/,
     +6X,'AVE. WINDSPEED= ',F5.1,//,
     +1X,'TIME',3X,'AIR TEMP.',2X,'WRAPT20',2X,'BARKT20',2X,
     +'BARKT3',2X,'BARKT37'/)
C
C     BEGINNING OF TIME LOOP
C
      DO 100 TIME=TO,ST,DT
C
C     CALL SUBROUTINES TO GET SFC HEAT LOSS
C
      DO 150 VERT=1,TOP
      CALL CONV(U,V,D,CPA,RHOA,KA,TA,T(RWRAP,VERT),CV,NU,RE,PR,HC)
      CALL RAD(EMIS,SBC,TA,T(RWRAP,VERT),R)
      G=(KW*(T(RWRAP-1,VERT)-T(RWRAP,VERT)))/((DR*RWRAP)
     +*ALOG(RWRAP/(RWRAP-1)))
      DTDT(RWRAP,VERT)=(((G-R-CV)/DR)/(RHOW*CPW))
150   CONTINUE
C
C     LOOP FOR HEAT CONDUCTION THRU WRAP AND TRUNK
C
      DO 999 VERT=2,TOP-1
      DO 200 RDS=RWRAP-1,2,-1
          IF(RDS.LE.RBARK)THEN
             K=KB
             KBLONG=KBLONG
             RHO=RHOB
             CP=CPB
          ELSEIF(RDS.GT.RBARK)THEN
             K=KW
             KBLONG=KW
             RHO=RHOW
             CP=CPW
          ENDIF
      TERM1=(K/(RHO*CP))
      TERM2=(T(RDS-1,VERT)-2*T(RDS,VERT)+T(RDS+1,VERT))/(DR**2)
      TERM3=(1/(DR*RDS))*((T(RDS-1,VERT)-T(RDS+1,VERT))/(2*DR))
      TERM4=(T(RDS,VERT+1)-2*T(RDS,VERT)+T(RDS,VERT-1))/(DZ**2)
      DTDT(RDS,VERT)=(TERM1*(TERM2+TERM3))+(KBLONG/(RHO*CP))*TERM4
200   CONTINUE
999   CONTINUE
C
C     UPDATE STATE VARIABLES VIA EULER
C
      DO 333 VERT=2,TOP-1
      DO 500 RDS=2,RWRAP
      T(RDS,VERT)=T(RDS,VERT) + DT*DTDT(RDS,VERT)
      TC(RDS,VERT)=T(RDS,VERT)-273.
      T(RDS,1)=TSOIL
```

```
      T(RDS,TOP)=TA
500   CONTINUE
      T(1,VERT)=T(2,VERT)
333   CONTINUE
C
C     WRITE TO OUTFILE
C
      MID=TOP/2
      INT=IFIX(TIME*(1/DT))
      IF(MOD(INT,900).EQ.0)THEN
      WRITE(51,1000)TIME,TCA,TC(RWRAP,MID),TC(RBARK,MID),
     +TC(RBARK,3),TC(RBARK,(TOP-2))
1000  FORMAT(' ',F6.0,5X,F6.2,5X,F6.2,5X,F6.2,5X,F6.2,5X,F6.2)
      ENDIF
C
C         FORCING FUNCTIONS
C
      TCA=AMP+(TAU*TIME)+TAMIN
      TA=TCA+273
      V=VAMP*(SIN(.167*TIME))+VXBAR
      TSOIL=TSOILI-(DTSOIL*TIME)
100   CONTINUE
      STOP
      END
C
C     SUBROUTINES
C
      SUBROUTINE RAD(EMIS,SBC,TA,T,R)
      REAL EMIS,SBC,TA,T,R
      R=4*EMIS*SBC*(TA**3)*(T-TA)
      RETURN
      END
C
C
      SUBROUTINE CONV(U,V,D,CPA,RHOA,KA,TA,T,CV,NU,RE,PR,HC)
      REAL U,V,D,CPA,GR,NUFREE,NUFRC,RHOA,KA,TA,T,CV,NU,RE,HC
      RE=(V*D)/U
      IF(V.LE.10.AND.V.GT.0)THEN
          NUFRC=0.62*(RE**.47)
      ELSEIF(V.LE.100.AND.V.GT.10)THEN
          NUFRC=0.17*(RE**.62)
      ELSEIF(V.LE.1000.AND.V.GT.100)THEN
          NUFRC=0.024*(RE**.81)
      ENDIF
C
C     FREE CONVECTION CALCULATION (WHEN V IS LOW)
C
      GR=((1/273)*980*(40**3)*(T-TA))/(U**2)
      NUFREE=0.58*(GR**.25)
C
C     CHOOSE APPROPRIATE NUSSELT NUMBER (FROM MONTEITH)
C
      IF((GR/RE**2).GT.16)THEN
         NU=NUFREE
```

```
ELSEIF((GR/RE**2).LT.0.1) THEN
   NU=NUFRC
ELSEIF(0.1.LT.(GR/RE**2).AND.(GR/RE**2).LT.16)THEN
   NU=(NUFRC+NUFREE)/2
ENDIF
HC=(KA*NU)/D
CV=HC*(T-TA)
RETURN
END
```

APPENDIX B

The following is a listing of the FORTRAN code for the microsprinkler irrigation simulation, which begins with a list of variables used throughout the program.

```
C       MARK RIEGER
C
C       MIS.FOR  MICROSPRINKLER IRRIGATION SIMULATION
C
C       LIST OF VARIABLES:
C
C       A=Y-INTERCEPT OF LINEAR TEMP. INCREASE
C       AMP=AMPLITUDE OF EXPON. TEMP. DECREASE FN
C       AMT=AMOUNT OF FRACTION INTERCEPTED ON WRAP SURFACE SECTION
C       AREA=SURFACE AREA OF WRAP (CM2)
C       B=SLOPE OF LINEAR TEMP. INCREASE FN
C       CATCH=FRACTION OF WATER INTERCEPTED BY WRAP
C       CPA=SPECIFIC HEAT OF AIR (CAL/KG*K)
C       CPB=    "           " BARK    "
C       CPH2O=  "             WATER   "
C       CPI=    "           " ICE     "
C       CPW=    "           " WRAP    "
C       CV=RATE OF CONVECTIVE HEAT LOSS(CAL/CM2 S)
C       D=CHARACTERISTIC DIMENSION (CM)
C       DICEDT=RATE OF ICE ACCRETION ON WRAP SURFACE (CM/S)
C       DTDT=TIME RATE OF CHANGE OF A VARIABLE
C       DTDTICE=TIME RATE OF CHANGE OF ICE TEMPERATURE (°C/S)
C       DTDTWF=   "    "   "    "   "   WATER  "          "
C       DT=DELTA T- TIME INCREMENT (S)
C       DR=RADIAL DISTANCE INCREMENT (CM)
C       DWV=MOLECULAR DIFFUSIVITY OF WATER VAPOR(CM2/S)
C       E=RATE OF EVAPORATIVE HEAT LOSS (CAL/CM2 S)
C       EMIS=EMISSIVITY WRAP SURFACE
C       FREEZ=RATE OF HEAT CONDUCTION FROM ICE-WATER INTERFACE THRU ICE
C       G=RATE OF HEAT CONDUCTION INTO OUTERMOST WRAP LAYER (CAL/CM2 S)
C       GR=GRASHOF NUMBER, USED IN FREE CONVECTION
C       GRAD=INITIAL GRADIENT OF TEMPERATURE THROUGH THE WRAP (°C/CM)
C       GBL=BOUNDARY LAYER CONDUCTANCE (MONTEITH,P. 135 "rv")
C       HC=CONVECTIVE HEAT TRANSFER COEF. (CAL/CM2 S K)
C       IR=RATE OF HEAT TRANSFER FROM IRRIGATION WATER (CAL/CM2 S)
C       KA=THERMAL CONDUCTIVITY AIR(CAL/S CM K)
C       KB=  "          "       BARK
C       KH2O=           "       WATER   "
C       KI=  "          "       ICE
C       KW=  "          "       WRAP
C       LEFT=FURTHEST SECTION OF WRAP ON LEFT SIDE COVERED WITH WATER
C       LHF=LATENT HEAT OF FUSION (CAL/CM3)
```

```
C       LHV=LATENT HEAT OF EVAPORATION (CAL/CM3)
C       NA=#MOLES WATER VAPOR IN AIR (SUBROUTINE EVAP)
C       NWF= "      "     "    " BOUNDARY LAYER OF SYSTEM
C       NUFRC=NUSSELT NUMBER FOR FORCED CONVECTION
C       NUFREE=NUSSELT NUMBER FOR FREE CONVECTION
C       PI=3.141592654
C       PR=PRANDTL NUMBER
C       PSA=SATURATION VAPOR PRESSURE OF AIR (KPA)
C       PSWF= "                    "       WATER FILM (KPA)
C       R=RADIATIVE HEAT TRANSFER FROM WATER/ICE(CAL/CM2 S)
C       QH2O=RATE OF HEAT CONDUCTION THRU WATER FILM ON WRAP (CAL/CM2 S)
C       QICEI= "   "   "      "        "  INNER ICE LAYER  "
C       QICEO= "   "   "      "        "  OUTER ICE LAYER  "
C       QWF=   "   "   "      "        "  WATER FILM ON ICE    "
C       RATE=IRRIGATION RATE (L/HR)
C       RE=REYNOLDS NUMBER
C       RH=RELATIVE HUMIDITY
C       RHOA=DENSITY OF AIR (KG/CM3)
C       RHOH2O=  "        WATER   "
C       RHOI=  "         ICE     "
C       RHOW=  "         WRAP    "
C       RHOB=  "         BARK    "
C       RIGHT=FURTHEST SECTION OF WRAP ON RIGHT SIDE COVERED WITH WATER
C       RICE= RADIUS TO OUTSIDE OF ICE (CM)
C       RWRAP= "                   WRAP
C       RBARK= "                   BARK
C       RTICE=RADIUS OF THE ICE LAYER (CM)
C       SBC=STEFAN-BOLTZMANN CONSTANT(1.355E-12CAL/CM2 S K4)
C       SC=SCHMIDT NUMBER
C       SH=SHERWOOD NUMBER
C       ST=STOP TIME (S)
C       TA=TEMPERATURE OF AIR (K)
C       TCA=TEMPERATURE OF AIR (C)
C       TH2O=    "          IRRIGATION WATER (K)
C       THAW=RATE OF HEAT CONDUCTION THRU WATER LAYER ON ICE (CAL/CM2 S)
C       THETA=INTEGER FOR # OF SECTIONS OF WRAP SURFACE IN CIRCUM. DIR.
C       TAMIN=MINIMUM AIR TEMP (°C)
C       TTMIN=TIME OF TAMIN (S)
C       TIME=TIME (S)
C       TICE=TEMPERATURE OF THE ICE LAYER (°K)
C       TO=STARTING TIME
C       TAU= EXTINCTION COEF. IN EXPON. TEMP DECREASE
C       TWF=TEMPERATURE OF THE WATER FILM (°K)
C       U=KINEMATIC VISCOSITY AIR (CM2/S)
C       V=WIND VELOCITY (CM/S)
C       VAMP=AMPLITUDE OF WINDSPEED VARIATION (CM/S)
C       VXBAR=MEAN WINDSPEED (CM/S)
C       WSA=SATURATION VAPOR DENSITY OF WATER/ICE SURFACE (GM/CM3)
C       WAA=  "          "      "     "   AIR (GM/CM3)
C       X=DELAY IN TIME FUNCTIONS
C       Z=DEPTH OF WATER FILM (CM)
C
C       DECLARATIONS ETC.
C
```

```
      REAL AMP,AMT,CATCH,CPA,CPB,CPH2O,CPI,CPW,CV,DICEDT
      REAL D,DR,DTDT,DTDTWF,DWV,E,EMIS,FREEZ,GRAD
      REAL HC,G,GBL,GR,IR,K,KA,KB,KH2O,KI,KW,LHV,LHF,NA,NWF,NUFREE
      REAL NUFRC,NU,PI,PR,PSA,PSWF,RATE,R,RDS,RE,RH,RHO,RHOA
      REAL RHOH2O,RHOB,RHOI,RHOW,RICE,RBARK,RWRAP,SBC,SC,SH,TA,T
      REAL TC,TAMIN,TAU,TH2O,THAW,TWF,U,V,WAA,WSA,WSWF,X,Z
      REAL TIME,TO,ST,DT,QICEI,QICEO,QH2O,QWF,VAMP,RHB,RHA,VXBAR
      REAL TH2OI,DTH2O,RICEI
      INTEGER FLAG,THETA,LEFT,RIGHT,INT
      DIMENSION T(0:50,0:11),TC(0:50,0:11),DTDT(0:50,0:11)
      DIMENSION RICE(0:11),DICEDT(0:11),DTDTWF(0:11),TWF(0:11)
      DIMENSION TICE(0:11),RTICE(0:11),DTDTICE(0:11)
      OPEN(UNIT=50,FILE='MIS27.DAT',STATUS='OLD')
      OPEN(UNIT=51,FILE='MIS27.OUT',STATUS='NEW')
      OPEN(UNIT=52,FILE='SFC27.DAT',STATUS='NEW')
      READ(50,*) TO,ST,DT,AMP,TAU,TAMIN,V,VAMP,VXBAR,
     +RH,RHA,RHB,TH2OI,DTH2O,RWRAP,RBARK,GRAD,EMIS,RATE,
     +KW,RHOW,CPW,KB,RHOB,CPB,RICEI
      CATCH=RWRAP
      CPA=241.9
      CPH2O=1000.
      CPI=450.
      D=13.
      DR=0.5
      DWV=.212
      KA=0.0000578
      KH2O=0.0013917
      KI=0.005019
      LEFT=8
      LHF=80.
      LHV=598.
      PI=3.141592654
      RHOA=0.000001304
      RHOH2O=0.00
      RHOI=0.00092
      RIGHT=4
      SBC=1.355E-12
      TIME=0.
      TCA=AMP+TAMIN
      TA=TCA+273
      THETA=11
      TH2O=TH2OI
      U=0.133
      Z=0.1

C
C     INITIALIZE TEMPS TO STARTING VALUES ("GRAD" GRADIENT THRU WRAP)
C
      DO 20 J=0,THETA
      DO 10 I=1,RWRAP
         TC(I,J)=GRAD-(GRAD/RWRAP*I)
         T(I,J)=TC(I,J)+273
10    CONTINUE
      TWF(J)=T(RWRAP,J)
```

```
      RICE(J)=RICEI
      TICE(J)=273.
20    CONTINUE

C
C     OUTPUT HEADINGS
C
      WRITE(51,700)KW,RHOW,CPW,KB,RHOB,CPB,RWRAP,RBARK,V,RH,TH2O
700   FORMAT(' ',10X,'COS-CORRECT IRRIGATION SIMULATION OUTPUT',//,6X,
     +'KW= ',F10.8,2X,'RHOW= ',F10.8,2X,'CPW= ',F5.1,/,
     +6X,'KB= ',F10.8,2X,'RHOB= ',F10.8,2X,'CPB= ',F5.1,/,
     +6X,'WRAP RADIUS(5mm)= ',F4.1,2X,'TRUNK RADIUS(5mm)= ',F4.1,/
     +6X,'WIND(CM/S)= ',F4.0,2X,'RH= ',F3.0,2X,'WATER TEMP= ',F4.0,//
     +,2X,'TIME',5X,'AIR TEMP.',4X,'TWF1',5X,'WRAPT1',5X,
     +'WRAPT6',4X,'BARKT6',4X,'BARKT1',4X,'BARKT3',/)
      WRITE(52,234)
234   FORMAT(' ','TIME',2X,'AIRT',2X,'RICE7',2X,'RICE8',2X,'RICE9',
     +2X,'RICE10',2X,'WRAPT7',2X,'WRAPT8',2X,'WRAPT9',2X,'WRAPT10',/)
C
C     BEGINNING OF TIME LOOP
C
      DO 100 TIME=TO,ST,DT
      DO 800 THETA=0,11
C
C     CALL SUBROUTINES TO GET SFC HEAT BALANCE
C
      CALL CONV(U,V,D,CPA,RHOA,KA,TA,T(RWRAP,THETA),TWF(THETA)
     +,THETA,LEFT,RIGHT,RWRAP,CV,RICE(THETA))
      CALL RAD(EMIS,SBC,TA,T(RWRAP,THETA),TWF(THETA),THETA
     +,LEFT,RIGHT,RWRAP,R)
      CALL IRIG(KH2O,TH2O,TWF(THETA),CPH2O,RATE,RICE(LEFT),
     +THETA,LEFT,RIGHT,IR,DR,RWRAP)
      CALL EVAP(U,V,D,DWV,TWF(THETA),TA,LHV,RH,THETA,LEFT,RIGHT,
     +E,RICE(THETA))
        G=(KW*(T((RWRAP-1),THETA)-T(RWRAP,THETA)))/((DR*RWRAP)
     +  *ALOG((DR*RWRAP)/((DR*RWRAP)-DR)))
      IF(THETA.GE.LEFT.OR.THETA.LE.RIGHT)THEN
          FLAG=0
        IF(TWF(THETA).LT.273.OR.RICE(THETA).GT.RICEI)THEN
           FLAG=1
           RTICE(THETA)=(DR*RWRAP)+(RICE(THETA)/2)
           CALL FREEZE(KI,KH2O,LHF,RHOI,TWF(THETA),T(RWRAP,THETA)
     +      ,RICE(THETA),RWRAP,THETA,DICEDT(THETA),DR,Z,
     +       TICE(THETA),RTICE(THETA))
        END IF
        IF(FLAG.EQ.1)THEN
          QICEO=KI*(TICE(THETA)-273)/((RICE(THETA)+(DR*RWRAP))
     +       *ALOG(((DR*RWRAP)+RICE(THETA))/RTICE(THETA)))
          QICEO=QICEO*((DR*RWRAP)+RICE(THETA))/RTICE(THETA)
          QICEI=KI*(T(RWRAP,THETA)-TICE(THETA))/
     +              (RTICE(THETA)*ALOG(RTICE(THETA)/(DR*RWRAP)))
          DTDTICE(THETA)=(QICEI-QICEO)/(RICE(THETA)/2)/(RHOI*CPI)
          DTDT(RWRAP,THETA)=((G-(QICEI*RTICE(THETA)/(DR*RWRAP)))/DR)
     +                      /(RHOW*CPW)
```

```
          QWF=KH2O*(273-TWF(THETA))/(((DR*RWRAP)+RICE(THETA)+Z)*
     +         ALOG(((DR*RWRAP)+RICE(THETA)+Z)/((DR*RWRAP)+RICE(THETA))))
          DTDTWF(THETA)=((QWF+IR-R-E-CV)/Z)/(RHOH2O*CPH2O)
        ELSEIF(FLAG.EQ.0)THEN
          QH2O=(KH2O*(T(RWRAP,THETA)-TWF(THETA)))/(((DR*RWRAP)+Z)*
     +     ALOG(((DR*RWRAP)+Z)/(DR*RWRAP)))
          DTDT(RWRAP,THETA)=((G-(QH2O*((DR*RWRAP)+Z)/(DR*RWRAP)))
     +     /DR)/(RHOW*CPW)
          DTDTWF(THETA)=((QH2O+IR-R-E-CV)/Z)/(RHOH2O*CPH2O)
        END IF
       ELSEIF(THETA.LT.LEFT.AND.THETA.GT.RIGHT)THEN
        DTDTWF(THETA)=0.0
        DTDT(RWRAP,THETA)=((G-R-CV)/DR)/(RHOW*CPW)
       ENDIF
800    CONTINUE
C
C      LOOPS FOR HEAT CONDUCTION THRU & AROUND WRAP AND TRUNK
C
       DO 200 RDS=RWRAP-1,2,-1
        DO 300 THETA=1,10
          IF(RDS.LE.RBARK)THEN
             K=KB
             RHO=RHOB
             CP=CPB
          ELSEIF(RDS.GT.RBARK)THEN
             K=KW
             RHO=RHOW
             CP=CPW
          ENDIF
        TERM1=(K/(RHO*CP))
        TERM2=(T(RDS+1,THETA)-2*T(RDS,THETA)+T(RDS-1,THETA))/(DR**2)
        TERM3=(1/(DR*RDS))*((T(RDS+1,THETA)-T(RDS-1,THETA))/(2*DR))
        TERM4=(1/(DR*RDS)**2)*((T(RDS,THETA+1)-2*T(RDS,THETA)+
      +T(RDS,THETA-1))/0.62831853**2)
        DTDT(RDS,THETA)=TERM1*(TERM2+TERM3+TERM4)
300    CONTINUE
200    CONTINUE
C
C      UPDATE STATE VARIABLES VIA EULER
C
       DO 500 THETA=1,10
       DO 600 RDS=2,RWRAP
          T(RDS,THETA)=T(RDS,THETA) + DT*DTDT(RDS,THETA)
          TC(RDS,THETA)=T(RDS,THETA)-273.
          T(RDS,0)=T(RDS,10)
          T(RDS,11)=T(RDS,1)
600    CONTINUE
       T(1,THETA)=(T(2,6)+T(2,1))/2
C       THE ABOVE MAKES MIDDLE CYLINDER AN AVE. OF FRONT & BACK TEMPS
       TWF(THETA)=TWF(THETA)+DT*DTDTWF(THETA)
       IF(TWF(THETA).LT.273.OR.RICE(THETA).GT.RICEI)THEN
          RICE(THETA)=RICE(THETA)+DT*DICEDT(THETA)
          TICE(THETA)=TICE(THETA)+DT*DTDTICE(THETA)
       ENDIF
```

```
500   CONTINUE
      TWF(0)=TWF(10)
      TWF(11)=TWF(1)
      RICE(0)=RICE(10)
      RICE(11)=RICE(1)
C
C     WRITE TO OUTFILE
C
      INT=IFIX(TIME*(1/DT))
      IF(MOD(INT,2400).EQ.0)THEN
      WRITE(51,1000)TIME,TCA,TWF(1),TC(RWRAP,1),TC(RWRAP,6),
     +TC(RBARK,6),TC(RBARK,1),TC(RBARK,3)
1000  FORMAT(' ',F6.0,5X,F6.2,5X,F6.2,5X,F6.2,5X,
     +F6.2,5X,F6.2,5X,F6.2,3X,F6.2)
      WRITE(52,123)TIME,TCA,RICE(7),RICE(8),RICE(9),RICE(10),
     +TC(RWRAP,7),TC(RWRAP,8),TC(RWRAP,9),TC(RWRAP,10)
123   FORMAT(' ',F6.0,1X,F5.1,1X,F8.4,1X,F8.4,1X,F8.4,1X,
     +F8.4,1X,F8.4,1X,F6.2,1X,F6.2,1X,F6.2)
      ENDIF
C
C     FORCING FUNCTIONS
C
      IF(TIME.LE.10800)THEN
         X=0.
      ELSEIF(TIME.GT.10800.AND.TIME.LE.36000)THEN
         X=10800.
         TAU=-.0001389
         TAMIN=-4.
         VAMP=40.
         VXBAR=175.
      ELSEIF(TIME.GT.36000)THEN
         X=36000.
         TAU=0.
         TAMIN=-7.2
         VAMP=40.
         VXBAR=130.
      ENDIF
         TCA=AMP+(TAU*(TIME-X))+TAMIN
         RH=RHA+RHB*(TIME)
         TA=TCA+273.
         V=VAMP*(SIN(.167*TIME))+VXBAR
         TH2O=TH2OI-(DTH2O*TIME)
100   CONTINUE
      STOP
      END
C
C     SUBROUTINES
C
      SUBROUTINE RAD(EMIS,SBC,TA,T,TWF,THETA,LEFT,RIGHT,RWRAP,R)
      REAL EMIS,SBC,TA,T,TWF,R,RWRAP
      INTEGER THETA,LEFT,RIGHT
      IF(THETA.LT.LEFT.AND.THETA.GT.RIGHT)THEN
         R=4*EMIS*SBC*(TA**3)*(T-TA)
      ELSEIF(THETA.GE.LEFT.OR.THETA.LE.RIGHT)THEN
```

```
         R=4*EMIS*SBC*(TA**3)*(TWF-TA)
       ENDIF
       RETURN
       END
C
C
       SUBROUTINE CONV(U,V,D,CPA,RHOA,KA,TA,T,TWF,THETA,
      +LEFT,RIGHT,RWRAP,CV,RICE)
       REAL U,V,D,CPA,GR,NUFREE,NUFRC,RHOA,KA,TA,TWF,T,CV
       REAL NU,RE,HC,RWRAP,RICE
       INTEGER THETA,LEFT,RIGHT
       RE=(V*(RICE+D))/U
       IF(V.LE.10.AND.V.GT.0)THEN
           NUFRC=0.62*(RE**.47)
       ELSEIF(V.LE.100.AND.V.GT.10)THEN
           NUFRC=0.17*(RE**.62)
       ELSEIF(V.LE.1000.AND.V.GT.100)THEN
           NUFRC=0.024*(RE**.81)
       ENDIF
C
C      FREE CONVECTION CALCULATION (WHEN V IS LOW)
C
       IF(THETA.LT.LEFT.AND.THETA.GT.RIGHT)THEN
       GR=((1/273)*980*(40**3)*(T-TA))/(U**2)
       ELSEIF(THETA.GE.LEFT.OR.THETA.LE.RIGHT)THEN
       GR=((1/273)*980*(40**3)*(TWF-TA))/(U**2)
       ENDIF
       NUFREE=0.58*(GR**.25)
C
C      CHOOSE APPROPRIATE NUSSELT NUMBER (FROM MONTEITH)
C
       IF((GR/RE**2).GT.16)THEN
          NU=NUFREE
       ELSEIF((GR/RE**2).LT.0.1) THEN
          NU=NUFRC
       ELSEIF(0.1.LT.(GR/RE**2).AND.(GR/RE**2).LT.16)THEN
          NU=(NUFRC+NUFREE)/2
       ENDIF
C      X=1.72*((RICE+D)*U/V)**0.5
       HC=(KA*NU)/(RICE+D)
       IF(THETA.LT.LEFT.AND.THETA.GT.RIGHT)THEN
          CV=HC*(T-TA)
       ELSEIF(THETA.GE.LEFT.OR.THETA.LE.RIGHT)THEN
          CV=HC*(TWF-TA)
       ENDIF
       RETURN
       END
C
C
       SUBROUTINE IRIG(KH2O,TH2O,TWF,CPH2O,RATE,RICE,
      +THETA,LEFT,RIGHT,IR,DR,RWRAP)
       REAL KH2O,TH2O,RATE,IR,TWF,CATCH,RICE,DR,RWRAP,AMT,AREA
       INTEGER THETA,LEFT,RIGHT
       IF(THETA.EQ.1)THEN
```

```
         AMT=0.31
       ELSEIF(THETA.EQ.2.OR.THETA.EQ.10)THEN
         AMT=0.25
       ELSEIF(THETA.EQ.3.OR.THETA.EQ.9)THEN
         AMT=0.095
       ELSEIF(THETA.EQ.4.OR.THETA.EQ.8)THEN
         AMT=0.05
       ENDIF
       CATCH=(((DR*RWRAP)+(RICE-0.4))*2)/260
       AREA=(((DR*RWRAP)+(RICE-0.4))*2)*3.14*40/10
C      "CATCH" IS THE AMOUNT OF WATER INTERCEPTED BY THE WRAP/ICE
C        WHERE 120 IS AN ASSUMED PATH WIDTH AT 1 METER TO APPROX.
C        THE MEASURED INITIAL INTERCEPTION VALUE =0.11
C      "AMT" IS THE COSINE-CORRECTED AMOUNT OF WATER PER THETA INCREMENT
C      "AREA" IS  THE SURFACE AREA OF A THETA INCREMENT
       IF(THETA.GE.LEFT.OR.THETA.LE.RIGHT)THEN
         IR=((((RATE*3.78/3600)*CATCH)*CPH2O*(TH2O-TWF))*AMT)/AREA
       ELSEIF(THETA.LT.LEFT.AND.THETA.GT.RIGHT)THEN
         IR=0.0
       ENDIF
       RETURN
       END
C
C
       SUBROUTINE EVAP(U,V,D,DWV,TWF,TA,LHV,RH,THETA,LEFT,RIGHT
      +,E,RICE)
       REAL U,V,D,DWV,RE,NA,NWF,LHV,X,PSA,PSWF,RH,TWF,TA,WSA,WAA,WSWF
       REAL E,SH,SC
       INTEGER THETA,LEFT,RIGHT
       SC=U/DWV
       RE=(V*(RICE+D))/U
C         PHILLIP'S EQN IS SH=2+(0.37*RE**0.6*SC**0.33)
C         THIS IS MONTEITH'S EQN, PAGE 138
       SH=(0.26*(RE**0.6)*(SC**0.33))
       PSA=EXP(24.2779-(6238.64/TA)-(0.344438*ALOG(TA)))
       PSWF=EXP(24.2779-(6238.64/TWF)-(0.344438*ALOG(TWF)))
       NA=(0.01*PSA)/(0.0821*TA)
       NWF=(0.01*PSWF)/(0.0821*TWF)
       WSA=NA*0.018
       WAA=WSA*(RH/100)
       WSWF=NWF*0.018
C       THIS FOR FLAT PLATE FROM MONTEITH
C      X=1.72*((RICE+D)*U/V)**0.5
       GBL=(DWV*SH)/(RICE+D)
       IF(THETA.GE.LEFT.OR.THETA.LE.RIGHT)THEN
         E=LHV*GBL*(WSWF-WAA)
       ELSEIF(THETA.LT.LEFT.AND.THETA.GT.RIGHT)THEN
         E=0.0
       ENDIF
       END
C
C
       SUBROUTINE FREEZE(KI,KH2O,LHF,RHOI,TWF,TWRAP,
      +RICE,RWRAP,THETA,DICEDT,DR,Z,TICE,RTICE)
```

```
 REAL DICEDT,KI,KH2O,LHF,RHOI,TWF,TWRAP,RICE,RWRAP,DR
 REAL FREEZ,THAW,Z,TICE,RTICE
 INTEGER THETA
 THAW=(KH2O/(LHF*RHOI*1000))*((273-TWF)/((RICE+(DR*RWRAP)+Z)
+*ALOG((RICE+(DR*RWRAP)+Z)/(RICE+(DR*RWRAP)))))
 THAW=THAW*(RICE+(DR*RWRAP)+Z)/(RICE+(DR*RWRAP))
 FREEZ=-1*((KI/(LHF*RHOI*1000))*((TICE-273)/
+((RICE+(DR*RWRAP))*ALOG((RICE+(DR*RWRAP))/(RTICE)))))
 DICEDT=FREEZ + THAW
 RETURN
 END
```

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BIOGRAPHICAL SKETCH

Mark Rieger was born in Columbus, Ohio in June of 1960. Shortly thereafter, he moved to Pittsburgh, Pennsylvania where he graduated from high school in 1978. Mark became a forestry major at West Virginia University following high school, but transferred to Penn State his sophomore year and became a student of horticulture. Mark graduated with honors from Penn State on 29 May 1982, and began working on a Master of Science project dealing with water relations of pecan seedlings at the University of Georgia on 1 June 1982. He began working on a Ph.D. project on freezing stress and freeze protection of young citrus trees directly following graduation at Georgia in June 1984. Mark will return to the University of Georgia as Assistant Professor of Horticulture in July 1987.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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